

## **Nova-NOTE-SIM-42**

June 30<sup>th</sup> 2004

# **Results of simulations of the Liquid Scintillator Detector**

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We present numerical results of the simulation of the liquid scintillator detector described in Off-Axis-NOTE-SIM-24 and the NOvA proposal.

The event generation and analysis is as described in the above documents. There are some minor modifications to previous numbers due to;

1. fixing of some minor bugs and minor improvements to the reconstruction and analysis programs,
2. a re-normalization of the light output to 35 pe at the far end of a strip using only hits that deposit the energy in a strip appropriate for a minimum ionizing particle at normal incidence,
3. the neutrino data has the anti-neutrino small beam components added, these were always there for the anti-neutrino data.

The simulation parameters are:

- Beam spectra for the NuMI medium energy beam configuration, generated by Mark Messier, available at <http://enrico1.physics.indiana.edu/messier/off-axis/spectra/>, are used.  
Both neutrino and anti-neutrino beams are simulated. The beam spectra assumed  $3.7 \cdot 10^{20}$  protons on target per year and a 1 kton detector. Event numbers are scaled to a 250 kton-year exposure of this beam. The Nova proposal used  $4.0 \cdot 10^{20}$  pot/year. To convert to the proposal numbers multiply all event numbers by 1.081 and the FOM numbers by 1.040.
- $\sin^2 2\theta_{23} = 1.0$
- The main analysis is for  $\Delta m^2 = 0.0025 \text{ eV}^2$ , some data are also given for  $\Delta m^2 = 0.0020$  and  $0.0015 \text{ eV}^2$ .
- $\sin^2 2\theta_{13} = 0.05$ . Results for other values of  $\sin^2 2\theta_{13}$  can be obtained by scaling the number of oscillated  $\nu_e$  events and the FOM1 values by the ratio of the  $\sin^2 2\theta_{13}$  values.
- No matter or CP violating effects are included.
- The detector was at 810 km from Fermilab and off-axis positions from 6 to 16 km were simulated for  $\Delta m^2 = 0.0025 \text{ eV}^2$ , 8 to 14 km for  $\Delta m^2 = 0.0020 \text{ eV}^2$  and 10,12 km for  $\Delta m^2 = 0.0015 \text{ eV}^2$ .

Totals of 300,000  $\nu_\mu$  CC, 500,000 NC, 100,000 beam  $\nu_e$  CC and 100,000 oscillated  $\nu_e$  CC events were generated for each of the training and test samples, and for

the neutrino and anti-neutrino beams. The events were generated flat in beam energy between 0.15 and 6 GeV for all except the NC sample which was generated between 0.15 and 20 GeV. The events were weighted with the appropriate beam spectra, NC/CC ratio and to allow for the different energy ranges generated. Finally an overall normalization was applied to give the expected number of  $\nu_\mu$  CC events from a 250 kton-year exposure. Note that the same event samples are used for all the off-axis position and  $\Delta m^2$  values analysed and thus that there is some correlation between the results presented.

The analysis required a reconstructed event, including a track found by the Hough transform method, and no more than two hits outside a containment volume, defined as 50cm from the transverse edges of the detector and 2m from the detector ends. The events then had the following cuts applied, the numerical values of which are given in table 1 for each off-axis position (except for those which remained constant and whose values are given in the list below).

1. event length (always  $>200\text{cm}$  and  $<1000\text{cm}$ )
2. total pulse height,
3. number of planes found on the Hough track within 20 planes from the vertex (always  $>3$ ),
4. fraction of the total hits included in the Hough track,
5. hits/plane on the Hough track (always  $> 1.5$ ),
6. cosine of the angle between the Hough track and the beam direction (always  $>0.8$ ),
7. the  $\log_{10}$  of the likelihood ratios. ( $\nu_\mu\text{CC} > -2$ ,  $\nu_e\text{beam} > -5$ )

The values of the cuts were optimized at each off-axis position to give the maximum value of FOM1 (signal/ $\sqrt{\text{background}}$ ). The main change required was in the total pulse height cut. As one moved to smaller off-axis positions the convolution of the oscillation function times the beam spectrum moved to higher average energies and thus the upper pulse height cut needed to be raised. The lower cut removed NC background and thus raising it improved the FOM1 at small off-axis positions where the background is larger. The difference in the Hough fraction cut between the neutrino and anti-neutrino data reflected the different  $y$  distributions and the higher fraction of events with a high energy lepton and low energy hadron showers. The change in the NC likelihood cut reflected the higher fraction of this background at small off-axis distances. The event length grew slowly with increasing average energy but reducing the cut at large off-axis distances produced almost no improvement in the FOM1 so it was kept constant. The other cuts were insensitive to position and neutrino type. The neutrino and anti-neutrino cuts were optimized separately but the maximum FOM1 occurred for approximately the same background in each case, only the signal size changing.

The optimizations at  $\Delta m^2=0.0020$  and  $0.0015 \text{ eV}^2$  were carried out independently of that at  $\Delta m^2=0.0025 \text{ eV}^2$ , but the optimum cuts were very close to those of the higher  $\Delta m^2$ . Although the peak of the oscillation probability moved down in energy the spread of selected energies after convolution with the beam spectrum was similar enough that the optimization was not significantly different at  $\Delta m^2=0.0020 \text{ eV}^2$ . However at  $\Delta m^2=0.0015 \text{ eV}^2$  the shift was sufficient to give minor differences in the optimal cuts at the larger off-axis position. The differences are given in the caption of table 1.

For  $\Delta m^2=0.0025$  eV $^2$  the peak value of FOM1 is at 8km off-axis but the value is quite flat between 8 and 10km. Matter effects and CP violation suggest larger off-axis positions. FOM1 is still acceptable at 12km off-axis but going further off-axis would result in a significant loss of sensitivity. Presently an off axis site at 12 km seems the best compromise for the detection of  $\nu_e$  appearance and the determination of the mass hierarchy.

	6km	8km	10km	12km	14km	16km
Neutrino pulse height	8000-20000	6000-16000	6000-14000	4000-14000	4000-14000	4000-14000
Neutrino Hough hit fraction	0.8	0.8	0.8	0.8	0.8	0.8
Neutrino NC likelihood ratio	-2	-2	-2	-2	-2	-2
Anti-neutrino pulse height	8000-20000	6000-16000	6000-14000	4000-12000	4000-12000	4000-12000
Anti-neutrino Hough hit fraction	0.7	0.7	0.7	0.7	0.7	0.7
Anti-neutrino NC likelihood ratio	-2	-2	-2	-2	0	0

**Table 1:** Cuts as a function of off-axis position for  $\Delta m^2=0.0025$  and  $0.0020$  eV $^2$ . At  $\Delta m^2=0.0015$  eV $^2$  and 12km off-axis the upper limit on the neutrino pulse height was 12000 and the anti-neutrino Hough hit fraction was 0.8

Results of the simulations and cuts are given for 6 off-axis positions (6,8,10,12,14,16 km) for neutrinos and anti-neutrinos with  $\Delta m^2=0.0025$  eV $^2$ , for 8,10,12,14 km off-axis for  $\Delta m^2=0.0020$  eV $^2$  and 10,12 km off-axis for  $\Delta m^2=0.0015$  eV $^2$ . For each data set there are three tables containing;

1. the background contribution from  $\nu_\mu$  CC, NC and  $\nu_e$  beam events (summed neutrino and anti-neutrino), the total signal, total background, FOM1, FOM2 (signal/ $\sqrt{(\text{signal}+\text{background})}$ ) and the signal efficiency, defined as the number of selected events divided by the total produced. The errors on the quantities in these tables are purely the statistical error due to the statistics of the MC generation.
2. the numbers of events remaining after each cut for neutrino and antineutrino events separately. The cuts are made sequentially and each row of these tables represents;
  - i. Total events in an unoscillated beam for a 250kton-year exposure and in the energy range generated.
  - ii. Total events after oscillations
  - iii. Number of events reconstructed, i.e. matched clusters are found in each view

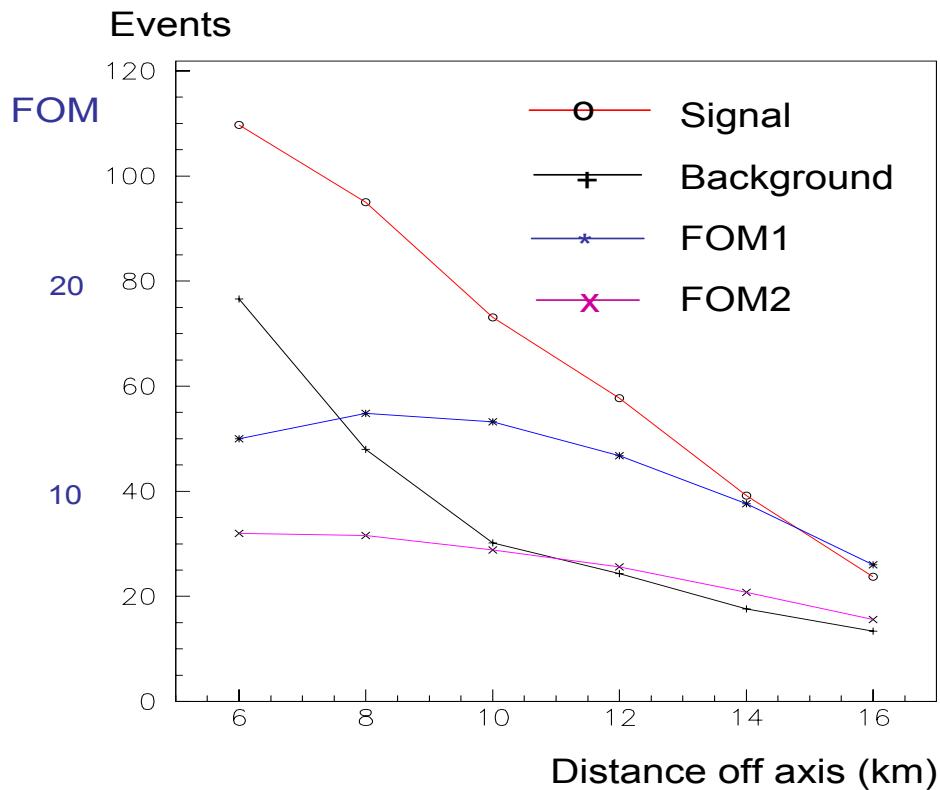
- iv. Number of events after the containment cut, i.e. with 2 or less hits outside the containment volume
  - v. Events left after the event length cut
  - vi. Events left after the pulse height cut
  - vii. Events left after the cut on the number of occupied planes in the Hough track for the 20 planes after the vertex
  - viii. Events left after the cut on the fraction of hits in the event contained in the Hough track
  - ix. Events left after the cut on the number of hits per plane in the Hough track
  - x. Events left after the cut on the angle between the Hough track and the beam direction
  - xi. Events left after the cut on the likelihood ratios, these are the final number of selected events
  - xii. Error on the final number of events from the MC statistics, a value of 0.0 means <0.05
  - xiii. Number of unweighted MC events finally selected.
3. the distributions of the 4 classes of events as a function of the truth neutrino energy, given in 30 bins from 0 to 6 GeV for  $\mu$  CC, NC, beam e CC and signal e oscillated, in that order,

Figure 1 shows the signal, background, FOM1 and FOM2 for the neutrino beam and Figure 2 for the anti-neutrino beam, at  $\Delta m^2=0.0025 \text{ eV}^2$ .

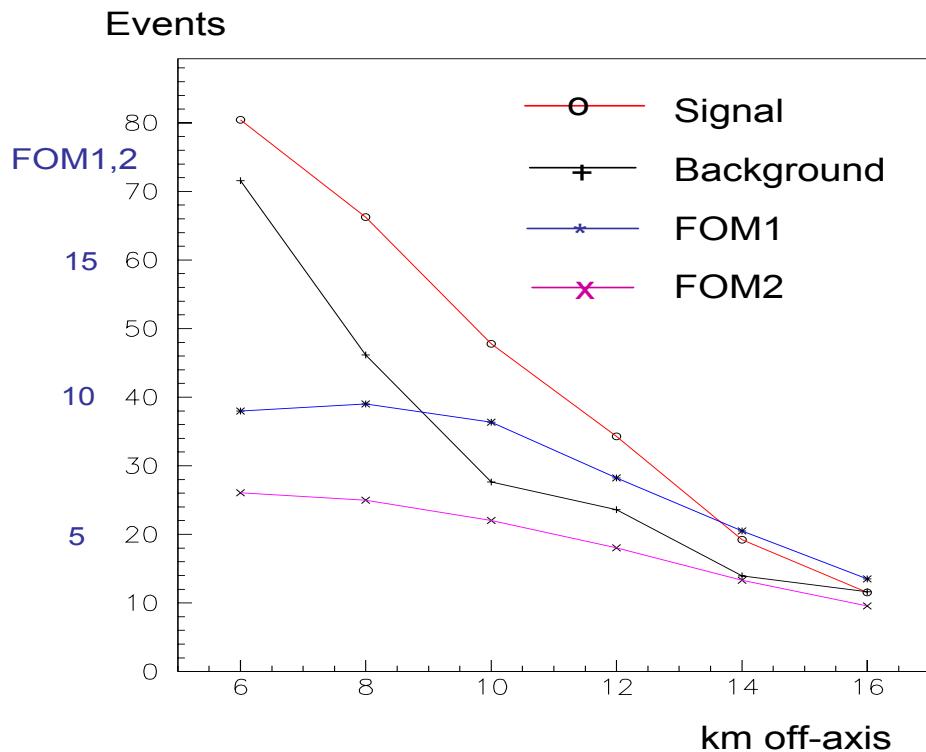
Figure 3 shows unoscillated and oscillated muon CC, NC and electron CC event spectra at 6, 12 and 16 km off axis for the neutrino beam and Figure 4 the same for the anti-neutrino beam, for  $\Delta m^2=0.0025 \text{ eV}^2$ . The incident neutrino and antineutrino components for each polarity beam are summed in the plots. Figure 5 shows the oscillated spectra for  $\Delta m^2=0.0025, 0.0020$  and  $0.0015 \text{ eV}^2$ .

Figures 6-11 show plots of the distributions used for the cuts at the extremes of the off axis positions (6 and 16km) and at the preferred site (12km) for the neutrino and anti-neutrino cases at a  $\Delta m^2$  of  $0.0025 \text{ eV}^2$ .

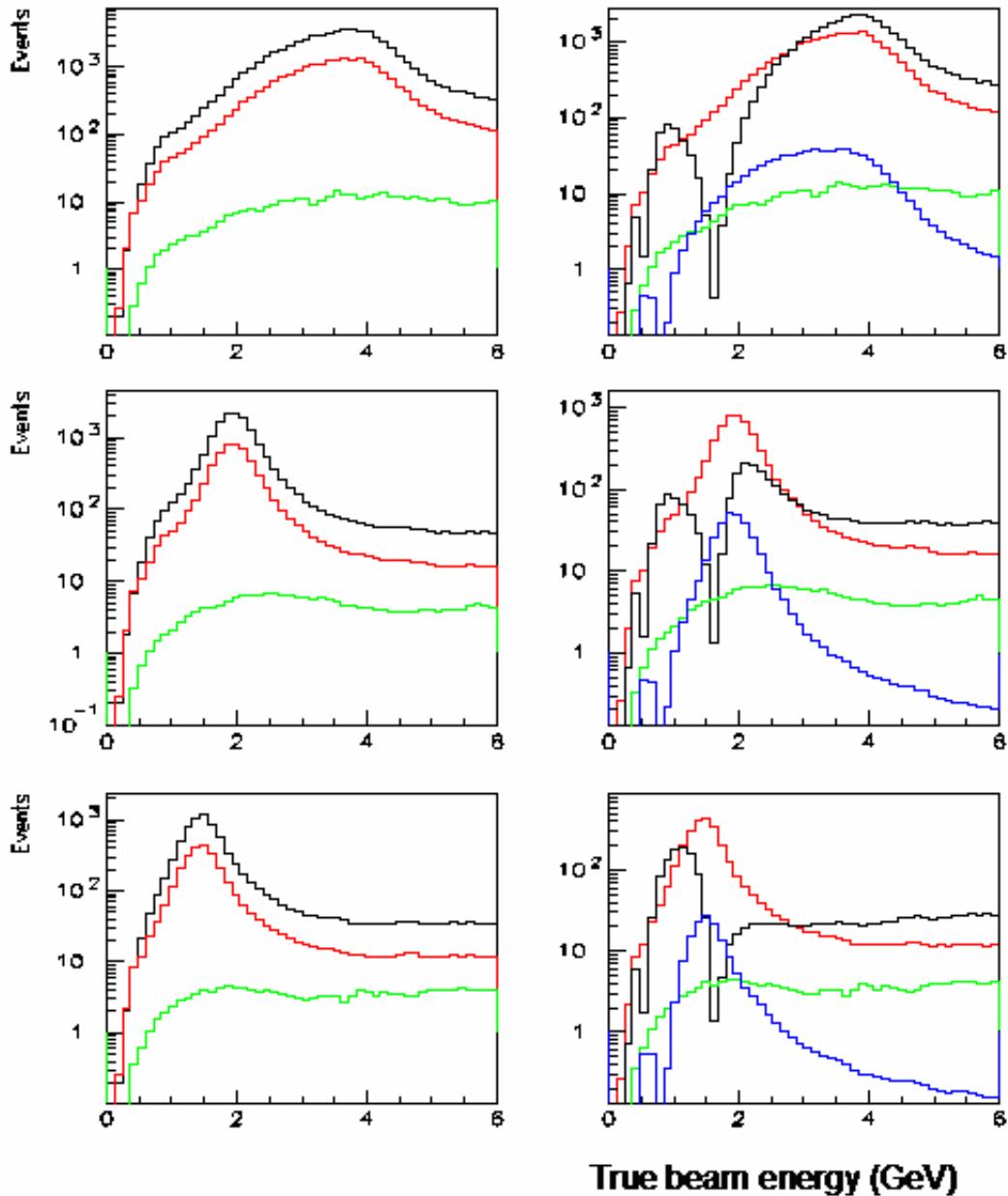
Figures 12 and 13 show the cut distributions at 12km off axis for  $\Delta m^2=0.0020 \text{ eV}^2$  and figures 14-15 for  $\Delta m^2=0.0015 \text{ eV}^2$ .



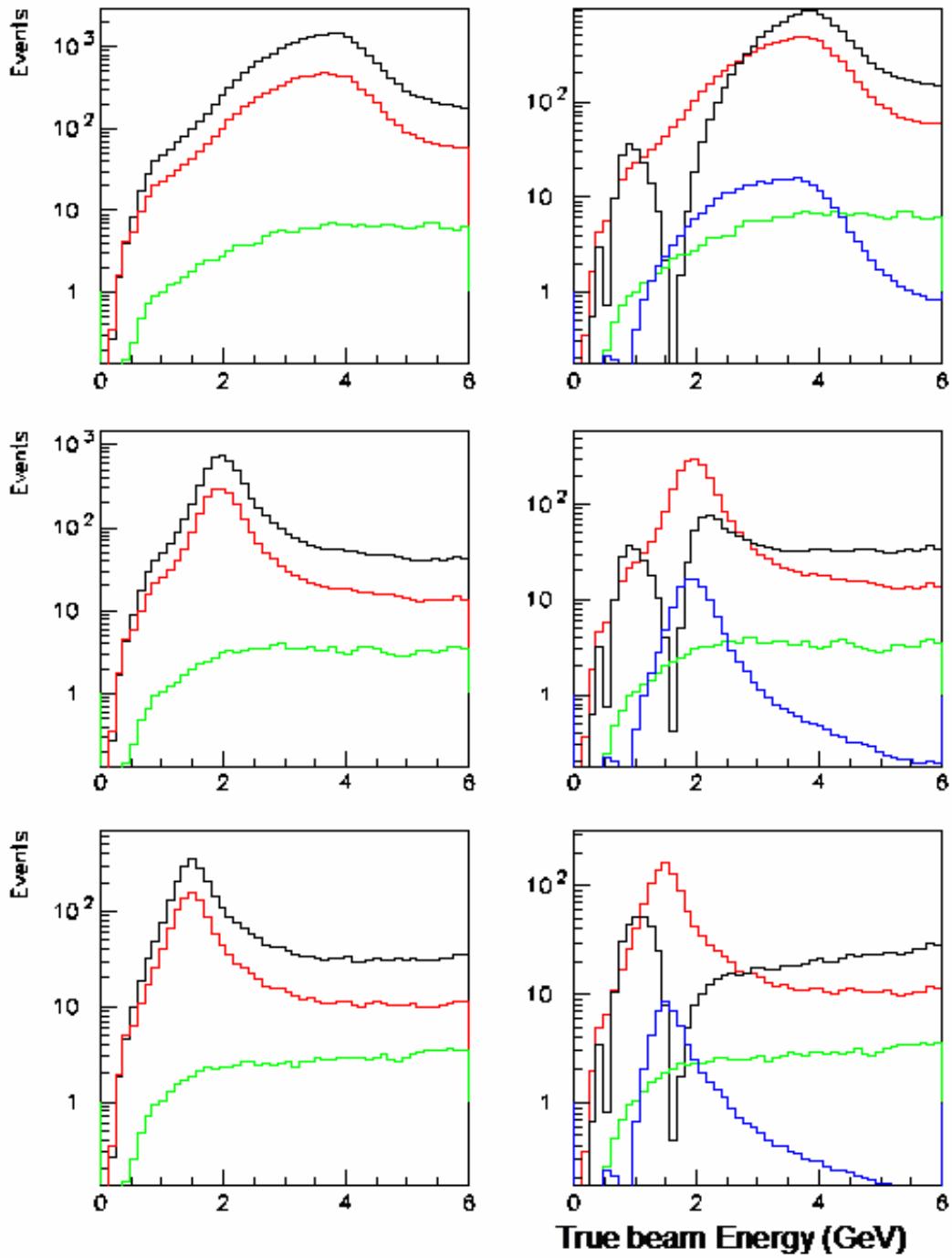
**Figure 1:** Neutrino FOM1,2, signal, background events as a function of off-axis distance.



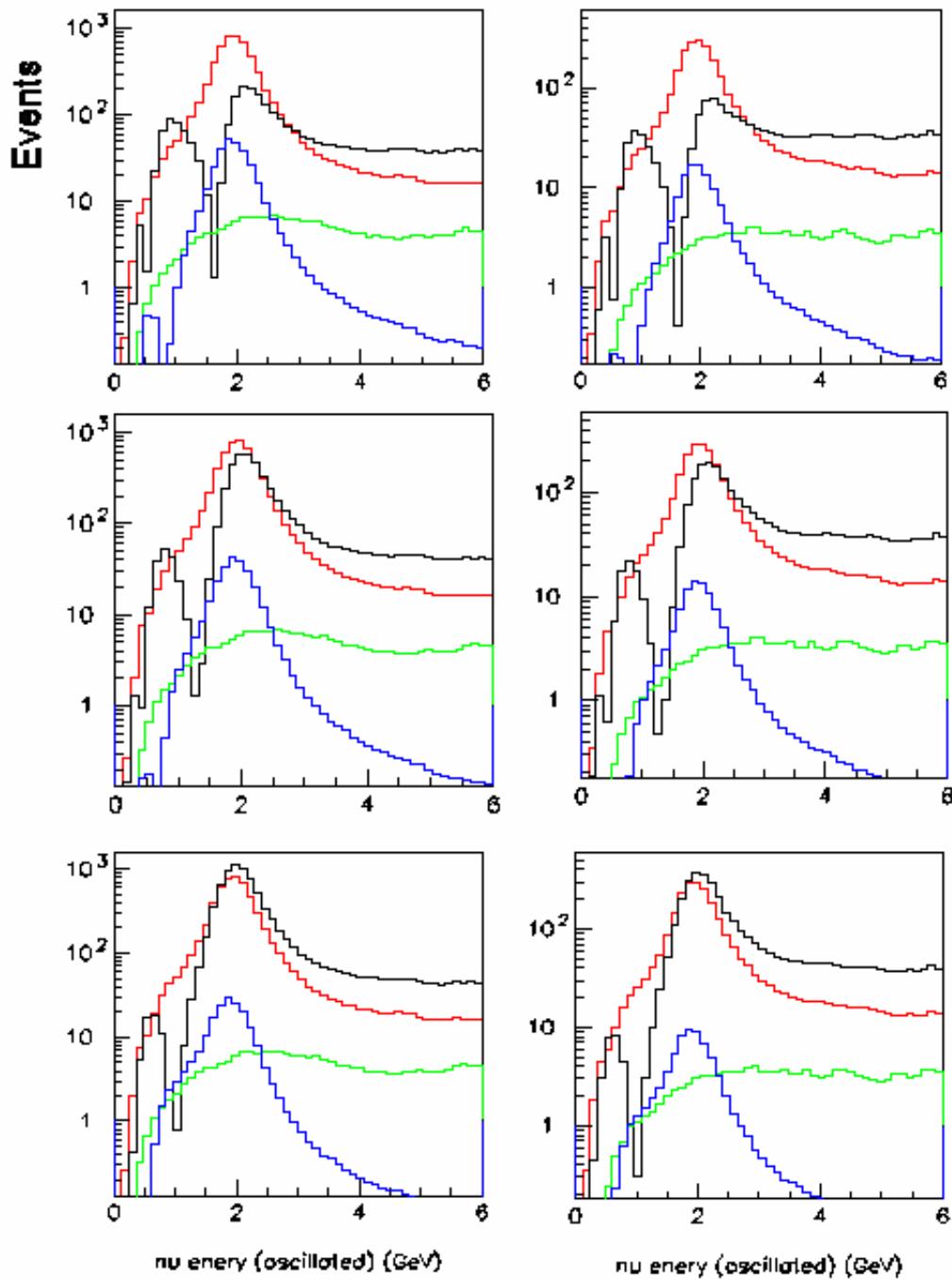
**Figure 2:** Anti-neutrino results plotted as a function of off-axis distance.



**Figure 3:** Neutrino beam spectra, unoscillated (left) and oscillated with  $\Delta m^2 = 0.0025 \text{ eV}^2$  and  $\sin^2 2\theta_{13} = 0.05$  (right). The top plots are for 6km off-axis, the center plots for 12km off-axis and the bottom plots for 16km off-axis. The black curve is for  $\nu_\mu$  CC events, the red curve NC events, green curve beam  $\nu_e$  CC events and the blue curve oscillated  $\nu_e$  CC events. The horizontal scale is the true beam neutrino energy in GeV.



**Figure 4** Anti-neutrino beam spectra, unoscillated (left) and oscillated with  $\Delta m^2=0.0025$  eV<sup>2</sup> and  $\sin^2 2\theta_{13}=0.05$  (right). The top plots are for 6km off-axis, the center plots for 12km of axis and the bottom plots for 16km off-axis. The black curve is for muon CC events, the red curve NC events, green curve beam electron CC events and the blue curve oscillated electron CC events. The horizontal scale is the true beam neutrino energy in GeV.



**Figure 5.** Oscillated neutrino energy spectra for the neutrino beam (left column) and anti-neutrino beam (right column) at 12 km off-axis for  $\Delta m^2=0.0025 \text{ eV}^2$  (top row),  $\Delta m^2=0.0020 \text{ eV}^2$  (middle row) and  $\Delta m^2=0.0015 \text{ eV}^2$  (bottom row). The colour coding is as in Figures 3 and 4.

**6km Off-axis,  $\Delta m^2=0.0025$  eV $^2$**

	$\mu$ CC	NC	e CC	Signal	Back	FOM1	FOM2	Eff.
<b>neutrino</b>	<b>3.9</b>	<b>25.6</b>	<b>47.1</b>	<b>109.7±1.3</b>	<b>76.6±2.5</b>	<b>12.5±0.3</b>	<b>8.0</b>	<b>0.16</b>
<b>Anti-neutrino</b>	<b>3.4</b>	<b>26.4</b>	<b>41.7</b>	<b>80.4±0.7</b>	<b>71.5±1.4</b>	<b>9.5±0.1</b>	<b>6.5</b>	<b>0.28</b>

## Neutrino

Test	$\nu_\mu$ CC	$\nu_\mu$ NC	$\nu_e$ beam	$\nu_e$ osc	$\bar{\nu}_\mu$ CC	$\bar{\nu}_\mu$ NC	$\bar{\nu}_e$ beam	$\bar{\nu}_e$ osc
Beam	58669.5	26245.0	375.0		874.2	705.0	21.0	
Beam osc	30882.4	26245.0	375.0	685.1	472.9	705.0	21.0	10.0
reconstructed	29708.9	17764.3	331.7	607.3	457.4	454.6	18.4	8.7
containment	18332.1	14246.9	245.9	456.3	272.1	353.0	14.0	6.7
event length	6316.4	11126.5	224.0	420.3	47.9	274.0	12.6	6.2
total ph	5272.3	3698.1	150.4	353.7	26.2	88.3	7.6	4.1
hough planes	4769.4	2822.1	141.7	334.9	24.4	66.4	7.4	4.0
hough fract	178.9	65.0	52.1	130.9	1.8	2.5	3.7	2.1
hough hits/pl	14.3	57.9	51.9	130.6	0.1	2.4	3.7	2.1
beam angle	12.8	57.7	51.9	130.3	0.1	2.4	3.7	2.1
likelihood	3.9	24.2	44.0	108.1	0.0	1.4	3.1	1.6
error	0.9	2.2	0.5	1.3	0.0	0.1	0.0	0.0
raw events	26.0	555.0	8253.0	8106.0	17.0	965.0	11993.0	12140.0

0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00

0.00 0.07 0.14 0.10 0.28 0.44 0.00 0.28 0.00 0.37

0.98 0.49 0.01 0.27 0.18 0.14 0.06 0.06 0.05 0.00

0.00 0.00 0.00 0.01 1.72 6.65 5.76 2.34 1.48 1.00

0.75 0.51 0.57 0.50 0.54 0.48 0.36 0.35 0.29 0.31

0.17 0.26 0.29 0.15 0.18 0.18 0.18 0.16 0.19 0.21

0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.03 0.15

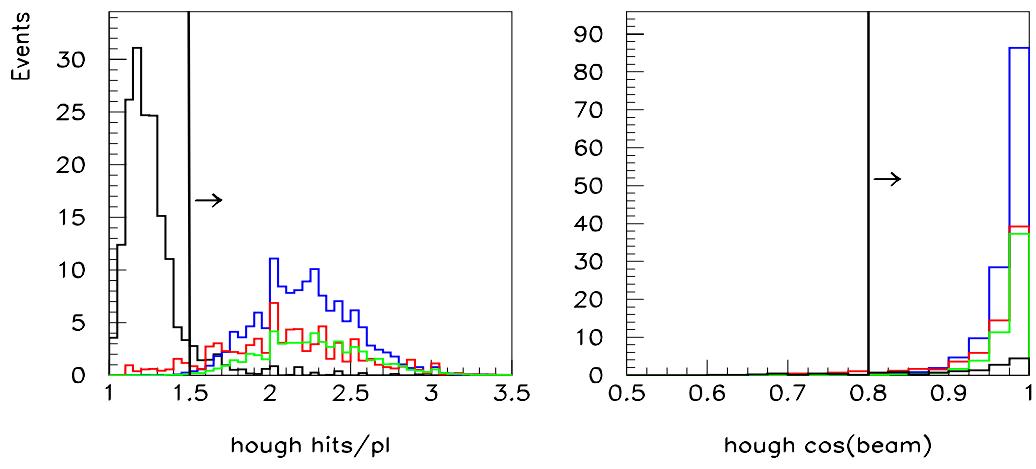
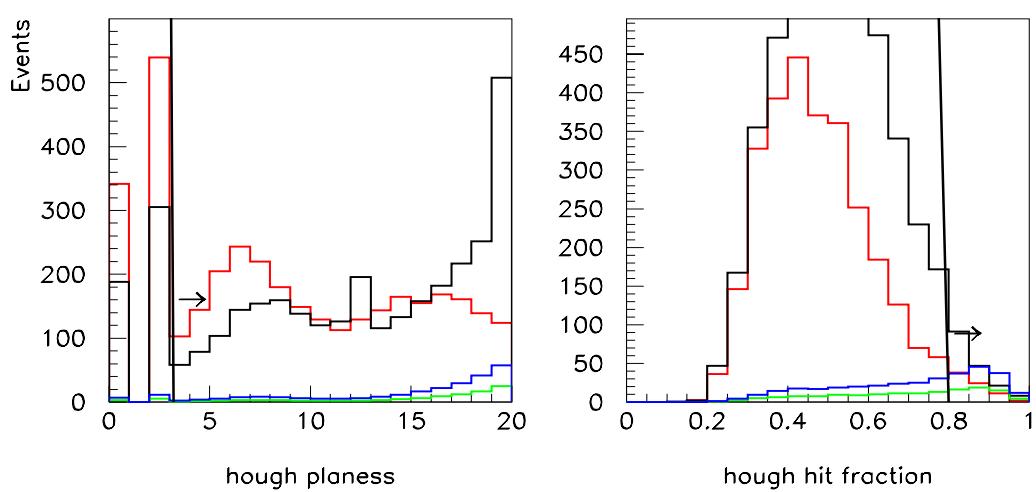
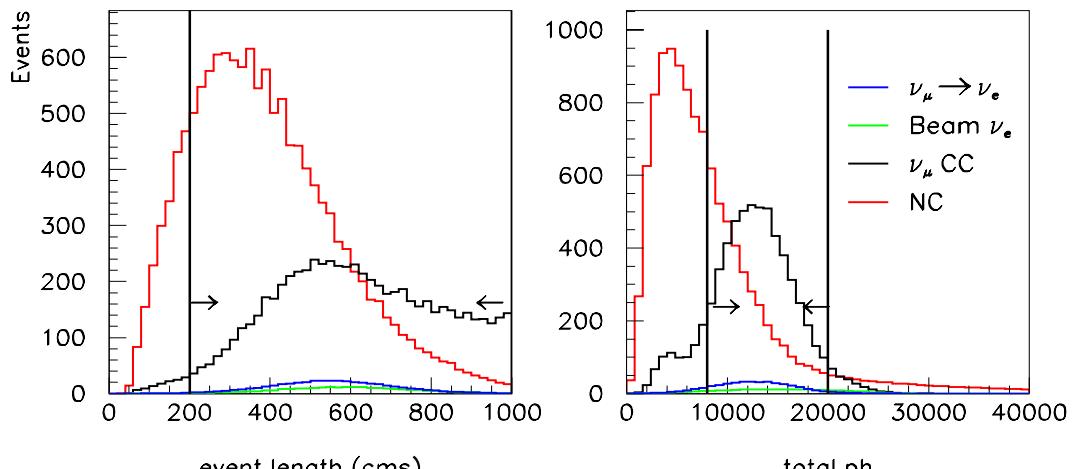
0.58 1.13 2.04 2.99 3.90 3.51 3.59 4.71 4.36 3.90

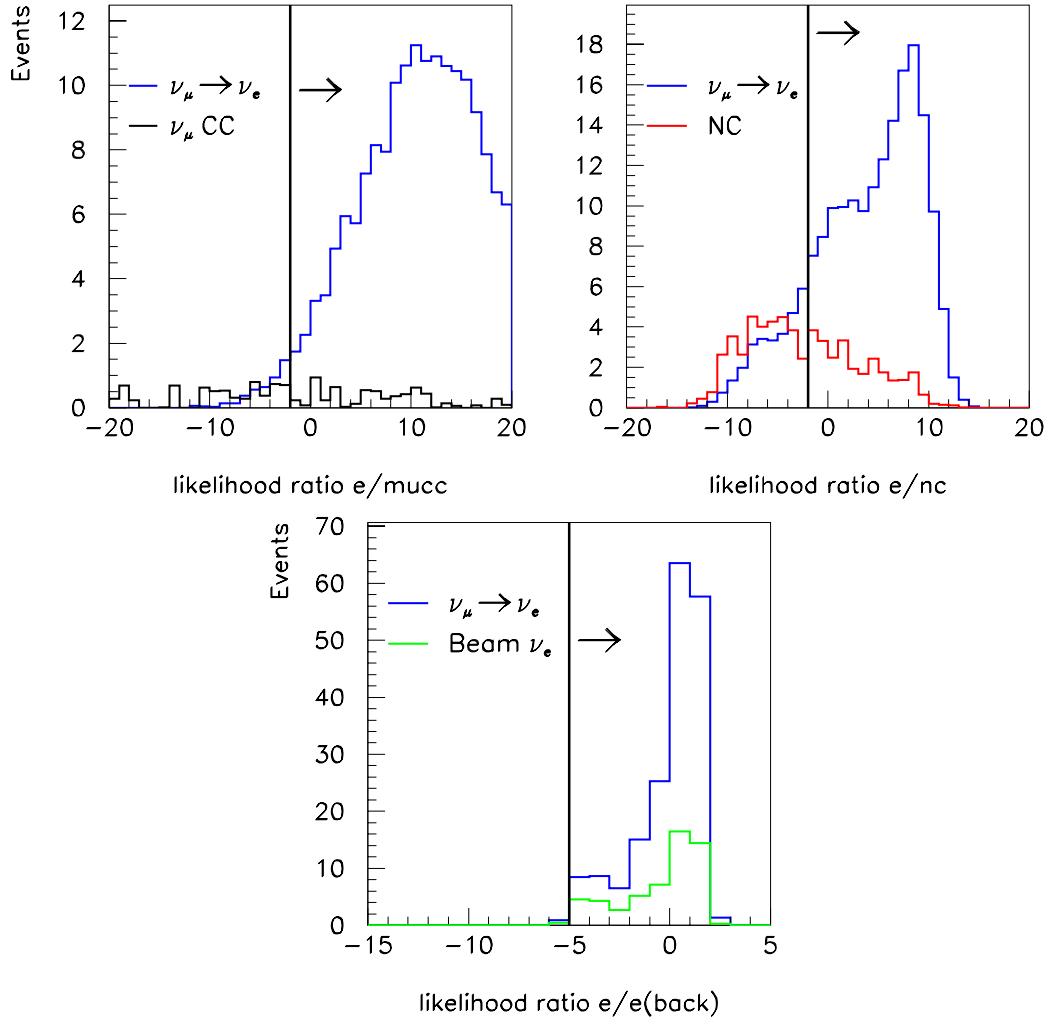
4.71 3.94 3.00 2.27 1.18 0.63 0.28 0.10 0.06 0.05

0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.01 0.06 0.38

1.32 3.33 6.10 8.99 10.85 12.45 12.73 12.57 12.17 10.73

8.24 5.19 2.62 1.16 0.48 0.19 0.08 0.02 0.01 0.01





**Figure 6:** Event distributions for the cut process at 6 km off-axis for neutrino beam events. The top 6 plots (previous page) are for the cuts on individual quantities described in the text, taken in sequence. The bottom three plots (this page) are the  $\log_{10}$  of the three ratios produced by the likelihood analysis. Events which lie in the regions NOT included by the arrows are rejected as  $\nu_e$  candidates. The black curve is for muon CC events, the red curve NC events, green curve beam electron CC events and the blue curve oscillated electron CC events.

## Anti-neutrino

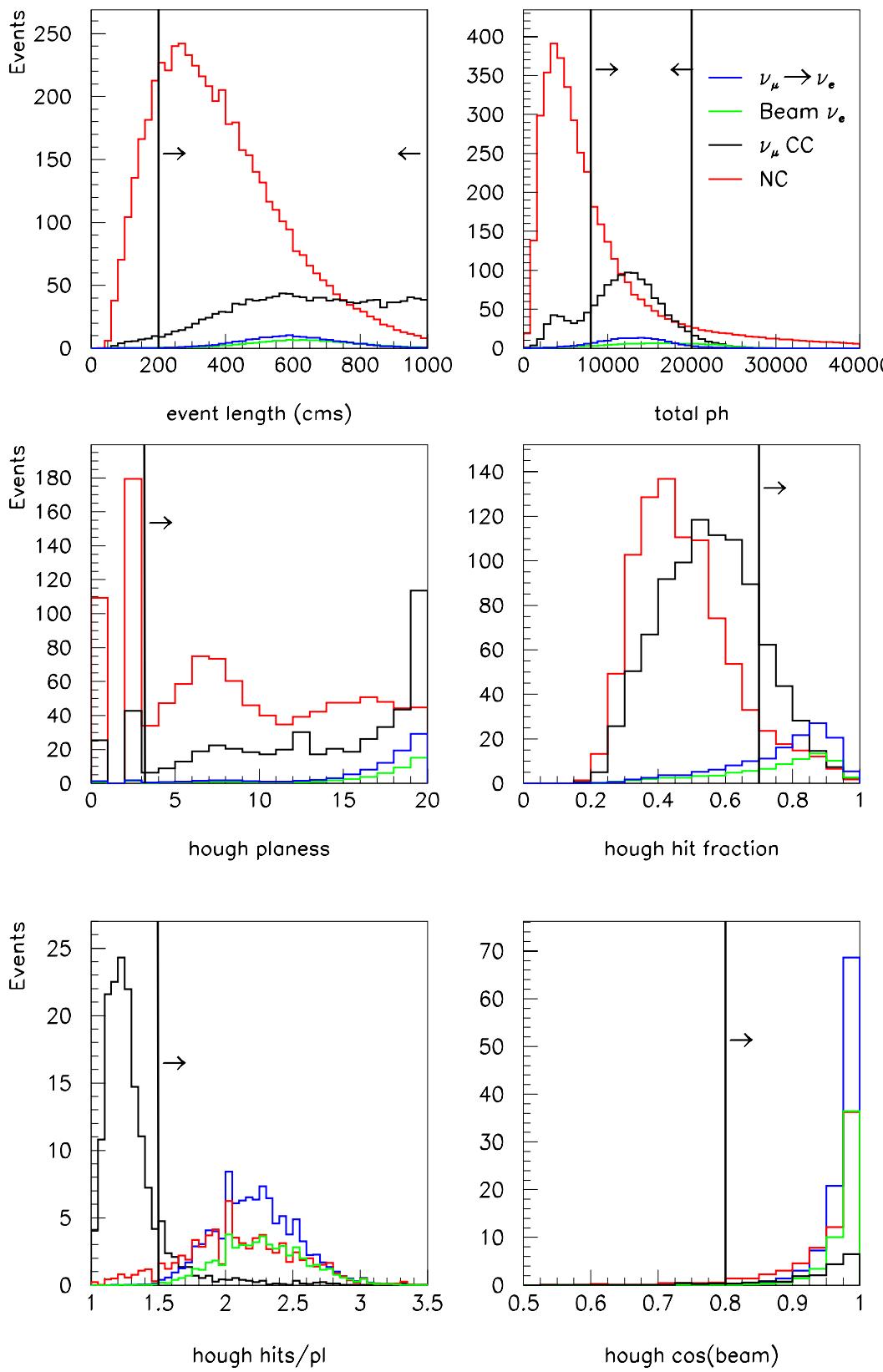
Test	$\nu_\mu$ CC	$\nu_\mu$ NC	$\nu_e$ beam	$\nu_e$ osc	$\bar{\nu}_\mu$ CC	$\bar{\nu}_\mu$ NC	$\bar{\nu}_e$ beam	$\bar{\nu}_e$ osc
beam	2104.6	1870.8	47.4		22639.3	9681.7	165.0	
beam osc	1104.2	1870.8	47.4	24.9	12068.2	9681.7	165.0	260.8
reconstructed	1052.5	1340.8	41.8	22.0	11690.2	5723.7	144.5	229.1
containment	644.5	1005.4	31.3	16.8	7121.7	4671.2	108.9	174.6
event length	230.7	799.6	28.1	15.2	1098.1	3503.2	98.5	159.9
total ph	139.4	279.4	16.7	9.2	857.3	914.0	64.8	138.6
hough planes	125.4	211.9	15.7	8.6	801.7	692.9	63.4	135.7
hough fract	15.5	12.8	8.4	4.9	151.8	66.7	44.5	97.8
hough hits/pl	2.6	11.7	8.4	4.8	14.9	62.3	44.4	97.5
beam angle	2.3	11.3	8.3	4.8	13.5	59.9	44.3	97.4
likelihood	0.7	4.7	6.2	3.0	2.7	21.7	35.5	77.4
error	0.1	0.2	0.1	0.0	0.5	1.2	0.3	0.7
raw events	121.0	1085.0	10651.0	10461.0	45.0	1431.0	15220.0	15215.0

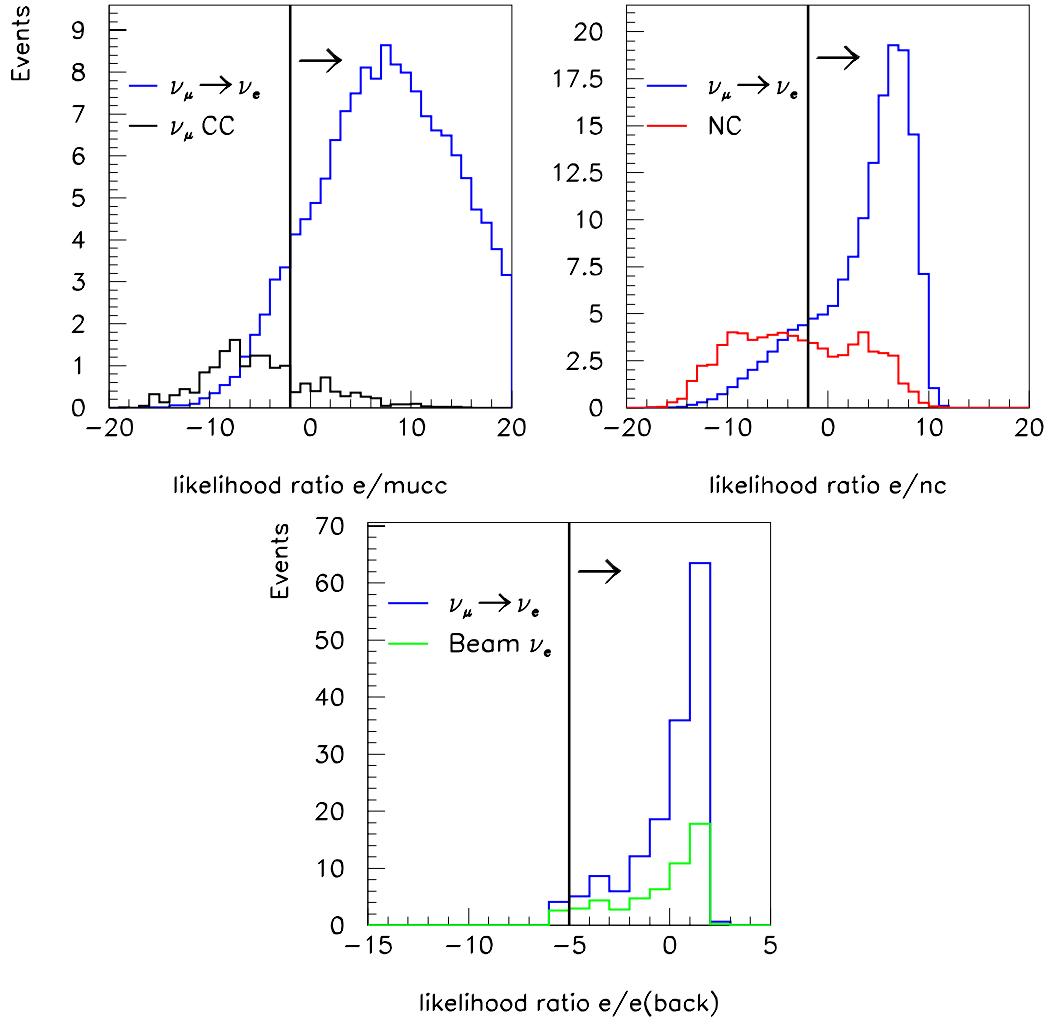
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00  
0.01 0.00 0.00 0.08 0.14 0.30 0.33 0.26 0.42 0.32  
0.31 0.33 0.18 0.15 0.20 0.16 0.06 0.08 0.03 0.06

0.00 0.00 0.00 0.06 1.17 5.77 4.89 2.06 1.72 1.24  
0.86 0.83 0.74 0.67 0.67 0.72 0.48 0.54 0.43 0.43  
0.42 0.43 0.39 0.31 0.30 0.33 0.32 0.25 0.23 0.19

0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.01 0.06  
0.29 0.68 1.30 2.23 2.99 3.14 3.72 3.79 4.50 4.17  
4.25 3.57 2.77 1.92 1.08 0.62 0.33 0.18 0.09 0.05

0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.02 0.16  
0.59 1.89 3.90 5.91 7.59 8.81 9.59 10.12 9.70 8.22  
6.42 4.00 1.97 0.89 0.36 0.16 0.07 0.03 0.01 0.01





**Figure 7:** Event distributions for the cut process at 6 km off-axis for anti-neutrino beam events. The top 6 plots (previous page) are for the cuts on individual quantities described in the text, taken in sequence. The bottom three plots (this page) are the  $\log_{10}$  of the three ratios produced by the likelihood analysis. Events which lie in the regions NOT included by the arrows are rejected as  $\nu_e$  candidates. The black curve is for muon CC events, the red curve NC events, green curve beam electron CC events and the blue curve oscillated electron CC events.

**8km Off-axis,  $\Delta m^2=0.0025$  eV $^2$**

	$\mu$ CC	NC	e CC	Signal	Back	FOM1	FOM2	Eff.
<b>neutrino</b>	<b>3.0</b>	<b>18.2</b>	<b>26.8</b>	<b>95.0±1.3</b>	<b>48.0±2.0</b>	<b>13.7±0.3</b>	<b>7.9</b>	<b>0.17</b>
<b>Anti-neutrino</b>	<b>2.5</b>	<b>18.7</b>	<b>24.9</b>	<b>66.3±0.7</b>	<b>46.1±1.0</b>	<b>9.7±0.1</b>	<b>6.2</b>	<b>0.29</b>

## Neutrino

Test	$\nu_\mu$ CC	$\nu_\mu$ NC	$\nu_e$ beam	$\nu_e$ osc	$\bar{\nu}_\mu$ CC	$\bar{\nu}_\mu$ NC	$\bar{\nu}_e$ beam	$\bar{\nu}_e$ osc
Beam	36419.5	16369.9	296.6		747.5	533.4	20.6	
Beam osc	14056.3	16369.9	296.6	552.1	387.1	533.4	20.6	9.0
reconstructed	13498.8	10575.3	262.2	490.0	374.3	335.0	18.0	7.9
containment	8818.6	8614.5	195.9	375.3	224.9	261.7	13.7	6.1
event length	3671.0	6538.4	178.4	346.6	42.4	201.3	12.3	5.6
total ph	3081.1	2585.9	100.8	310.2	20.9	74.3	5.4	3.8
hough planes	2809.3	1944.5	93.5	289.3	19.7	54.6	5.3	3.6
hough fract	253.7	80.7	34.8	117.5	3.1	2.7	2.7	1.9
hough hits/pl	12.7	58.6	34.4	116.4	0.1	2.4	2.6	1.9
beam angle	9.2	56.0	34.2	115.5	0.1	2.3	2.6	1.9
likelihood	3.0	17.2	24.9	93.7	0.0	1.0	1.9	1.3
error	0.7	1.8	0.3	1.3	0.0	0.0	0.0	0.0
raw events	36.0	580.0	6159.0	6169.0	28.0	910.0	8532.0	8580.0

0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
0.07	0.21	0.11	0.83	0.23	0.41	0.53	0.22	0.21
0.06	0.00	0.00	0.02	0.00	0.02	0.00	0.00	0.00

0.00	0.00	0.00	1.24	7.67	2.96	1.07	0.65	0.51
0.29	0.24	0.32	0.16	0.27	0.28	0.17	0.20	0.19
0.19	0.20	0.19	0.17	0.16	0.08	0.10	0.12	0.09

0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.24
1.61	2.46	3.01	3.28	3.69	3.09	3.25	2.28	1.39
0.37	0.22	0.10	0.05	0.03	0.04	0.02	0.01	0.00

0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.07	0.43
5.88	9.91	14.31	17.81	17.49	14.13	8.00	3.08	1.04
0.10	0.03	0.02	0.01	0.00	0.00	0.00	0.00	0.00

## Anti-neutrino

Test	$\nu_\mu$ CC	$\nu_\mu$ NC	$\nu_e$ beam	$\nu_e$ osc	$\bar{\nu}_\mu$ CC	$\bar{\nu}_\mu$ NC	$\bar{\nu}_e$ beam	$\bar{\nu}_e$ osc
beam	1851.1	1422.8	47.5		13593.0	6243.7	136.2	
Beam osc	926.8	1422.8	47.5	23.0	5389.9	6243.7	136.2	204.4
Reconstructed	881.8	995.6	41.9	20.3	5217.5	3515.2	119.3	179.6
containment	547.6	754.4	31.4	15.7	3338.8	2881.1	90.3	138.7
event length	204.3	594.5	28.3	14.1	704.7	2110.0	81.8	127.3
total ph	101.2	225.9	13.8	9.4	575.0	683.5	40.7	114.8
hough planes	90.8	167.5	12.8	8.7	544.8	507.6	39.6	111.6
hough fract	18.9	15.2	6.9	5.0	179.2	67.9	27.8	80.8
hough hits/pl	2.5	12.6	6.7	4.9	11.5	57.0	27.5	80.1
beam angle	1.8	11.2	6.6	4.7	9.5	50.3	27.4	79.6
likelihood	0.5	3.8	4.4	2.9	2.0	14.9	20.5	63.4
error	0.0	0.1	0.0	0.0	0.3	0.9	0.2	0.7
raw events	142.0	1153.0	8252.0	8316.0	52.0	1546.0	11528.0	11521.0

0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00

0.01 0.01 0.09 0.43 0.36 0.42 0.49 0.22 0.16 0.05

0.07 0.04 0.04 0.03 0.02 0.03 0.01 0.02 0.01 0.01

0.00 0.00 0.04 0.68 5.19 2.93 1.25 0.80 0.77 0.57

0.49 0.52 0.43 0.41 0.40 0.46 0.30 0.45 0.31 0.35

0.36 0.32 0.32 0.22 0.28 0.20 0.20 0.23 0.14 0.12

0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.03 0.21 0.59

1.17 1.65 2.28 2.87 3.02 3.10 3.34 2.80 1.84 0.94

0.50 0.25 0.12 0.08 0.06 0.04 0.02 0.02 0.01 0.00

0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.04 0.39 1.55

3.75 6.47 9.28 11.97 12.51 9.82 6.07 2.77 1.03 0.35

0.12 0.05 0.02 0.01 0.01 0.00 0.00 0.00 0.00 0.00

**10 km Off-axis,  $\Delta m^2=0.0025$  eV $^2$**

	$\mu$ CC	NC	e CC	Signal	Back	FOM1	FOM2	Eff.
<b>neutrino</b>	<b>1.7</b>	<b>12.0</b>	<b>16.5</b>	<b>73.1±1.2</b>	<b>30.2±1.3</b>	<b>13.3±0.4</b>	<b>7.2</b>	<b>0.17</b>
<b>Anti-neutrino</b>	<b>0.9</b>	<b>12.0</b>	<b>14.6</b>	<b>47.8±0.6</b>	<b>27.5±0.6</b>	<b>9.1±0.2</b>	<b>5.5</b>	<b>0.28</b>

Neutrino

Test	$\nu_\mu$ CC	$\nu_\mu$ NC	$\nu_e$ beam	$\nu_e$ osc	$\bar{\nu}_\mu$ CC	$\bar{\nu}_\mu$ NC	$\bar{\nu}_e$ beam	$\bar{\nu}_e$ osc
beam	22858.2	10593.9	229.0		597.5	434.5	20.6	
beam osc	5758.2	10593.9	229.0	426.6	289.2	434.5	20.6	7.7
reconstructed	5504.9	6559.6	202.4	379.0	279.4	269.8	18.0	6.7
containment	3749.1	5369.2	152.4	294.2	170.3	210.7	13.6	5.2
event length	1839.7	3967.3	138.4	270.5	35.6	161.4	12.3	4.8
total ph	1383.7	1176.9	67.7	234.6	14.4	51.4	4.1	2.9
hough planes	1278.3	883.0	62.5	217.8	13.6	37.6	3.9	2.9
hough fract	217.8	44.6	24.0	93.7	2.7	1.9	2.0	1.5
hough hits/pl	8.5	32.5	23.6	92.1	0.1	1.7	2.0	1.5
beam angle	5.1	31.3	23.3	90.7	0.1	1.6	2.0	1.5
likelihood	1.7	11.2	15.2	72.1	0.0	0.8	1.3	1.0
error	0.3	1.3	0.2	1.2	0.0	0.0	0.0	0.0
raw events	43.0	552.0	4795.0	4922.0	23.0	858.0	6389.0	6406.0

0.00 0.00 0.00 0.00 0.00 0.01 0.00 0.00 0.00 0.03  
 0.27 0.54 0.10 0.57 0.10 0.05 0.02 0.00 0.01 0.01  
 0.03 0.00 0.00 0.00 0.00 0.01 0.00 0.00 0.01 0.00

0.00 0.00 0.09 4.93 2.58 0.66 0.40 0.31 0.24 0.25  
 0.21 0.17 0.21 0.12 0.14 0.19 0.10 0.16 0.12 0.22  
 0.16 0.23 0.07 0.12 0.10 0.03 0.06 0.07 0.05 0.04

0.00 0.00 0.00 0.00 0.00 0.00 0.01 0.20 0.77 1.53  
 2.04 2.56 2.78 2.63 2.06 0.95 0.48 0.20 0.13 0.06  
 0.02 0.02 0.01 0.01 0.01 0.01 0.01 0.00 0.00 0.00

0.00 0.00 0.00 0.00 0.00 0.00 0.04 0.40 2.09 7.24  
 16.00 20.55 15.30 7.61 2.70 0.82 0.24 0.05 0.02 0.01  
 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00

## Anti-neutrino

Test	$\nu_\mu$ CC	$\nu_\mu$ NC	$\nu_e$ beam	$\nu_e$ osc	$\bar{\nu}_\mu$ CC	$\bar{\nu}_\mu$ NC	$\bar{\nu}_e$ beam	$\bar{\nu}_e$ osc
beam	1561.7	1184.4	46.0		8082.8	4209.8	105.8	
Beam osc	738.5	1184.4	46.0	20.5	2166.4	4209.8	105.8	149.2
reconstructed	700.7	819.7	40.5	18.1	2093.9	2271.4	92.7	130.7
containment	443.1	621.0	30.4	14.0	1376.2	1858.5	70.5	102.4
event length	173.9	486.5	27.3	12.6	389.7	1345.1	64.0	94.5
total ph	69.4	157.3	10.5	7.6	290.3	351.3	26.6	83.4
hough planes	62.4	116.2	9.7	7.1	277.2	257.6	25.8	80.9
hough frac	16.3	11.5	5.2	4.1	127.3	35.9	18.2	59.5
hough hits/pl	1.9	9.4	5.1	4.0	5.4	29.8	17.9	58.4
beam angle	1.3	8.3	5.0	3.8	4.2	25.9	17.7	57.9
likelihood	0.3	3.1	3.0	2.4	0.6	8.9	11.6	45.4
error	0.0	0.1	0.0	0.0	0.1	0.6	0.1	0.6
raw events	133.0	1094.0	6426.0	6549.0	40.0	1485.0	8673.0	8802.0

0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00  
 0.07 0.05 0.13 0.25 0.15 0.05 0.04 0.04 0.03 0.02  
 0.02 0.01 0.01 0.01 0.01 0.01 0.01 0.00 0.00 0.00

0.00 0.00 0.30 2.23 1.89 0.88 0.66 0.51 0.43 0.35  
 0.33 0.35 0.27 0.34 0.29 0.30 0.26 0.34 0.29 0.24  
 0.33 0.29 0.24 0.20 0.18 0.10 0.13 0.13 0.09 0.08

0.00 0.00 0.00 0.00 0.00 0.00 0.01 0.14 0.59 1.12  
 1.52 1.94 2.36 2.24 2.11 1.23 0.66 0.39 0.14 0.07  
 0.05 0.03 0.02 0.02 0.01 0.01 0.01 0.01 0.01 0.00

0.00 0.00 0.00 0.00 0.00 0.00 0.02 0.28 1.46 4.44  
 9.60 12.71 10.10 5.61 2.35 0.81 0.25 0.08 0.03 0.01  
 0.01 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00

## 12km Off-axis, $\Delta m^2 = 0.0025$ eV $^2$

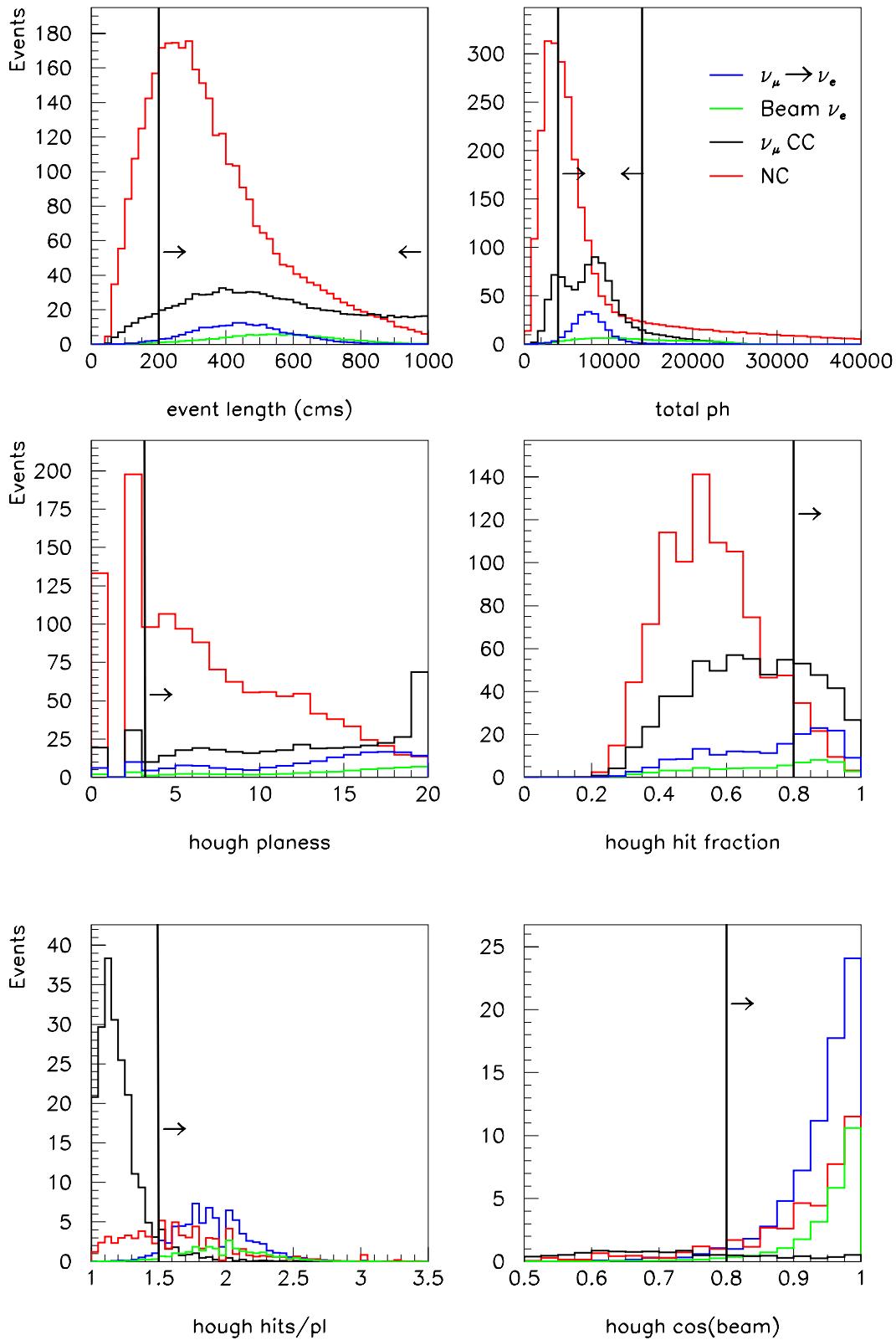
	$\mu$ CC	NC	e CC	Signal	Back	FOM1	FOM2	Eff.
<b>neutrino</b>	<b>1.1</b>	<b>10.5</b>	<b>12.7</b>	<b><math>57.7 \pm 1.0</math></b>	<b><math>24.3 \pm 1.0</math></b>	<b><math>11.7 \pm 0.3</math></b>	<b>6.4</b>	<b>0.18</b>
<b>Anti-neutrino</b>	<b>0.8</b>	<b>12.3</b>	<b>10.6</b>	<b><math>34.3 \pm 0.4</math></b>	<b><math>23.7 \pm 0.5</math></b>	<b><math>7.1 \pm 0.1</math></b>	<b>4.5</b>	<b>0.28</b>

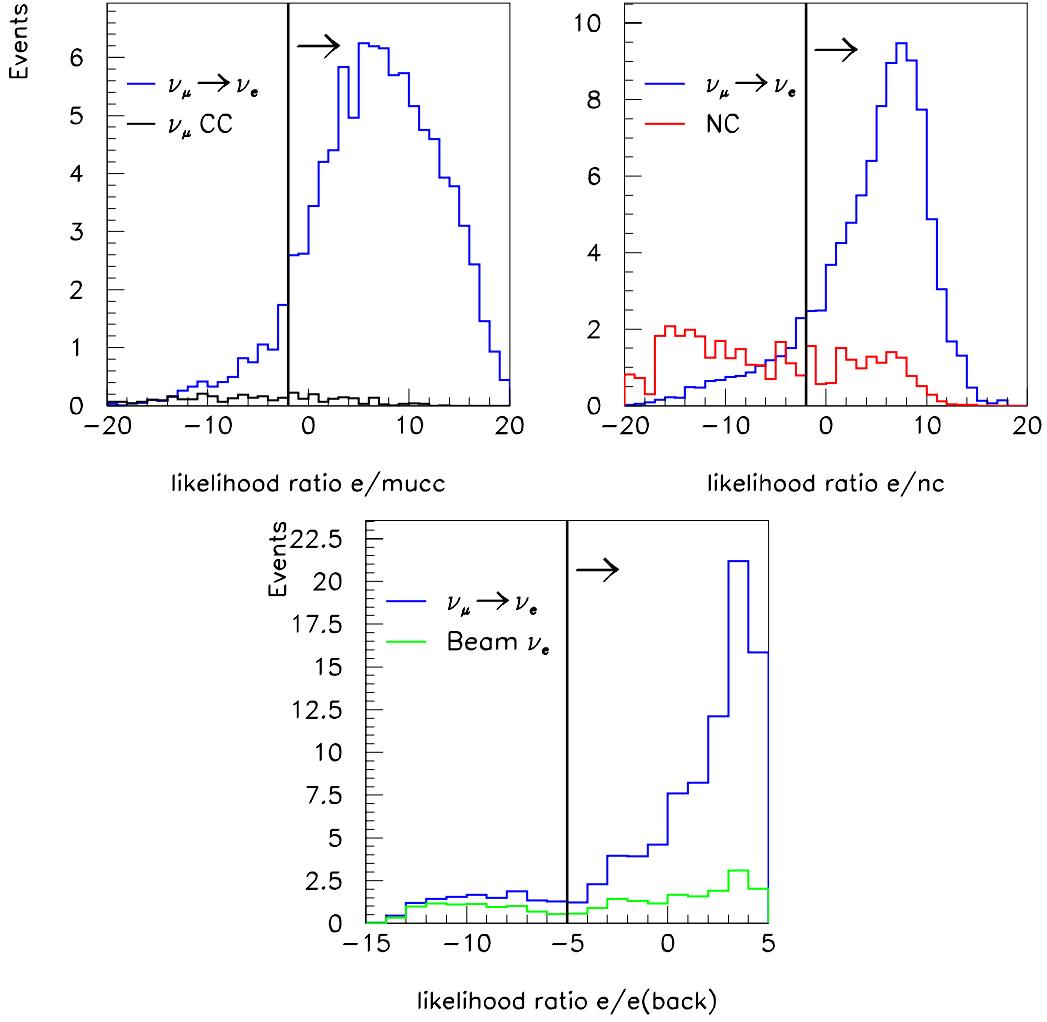
# Neutrino

Test	$\nu_\mu$ CC	$\nu_\mu$ NC	$\nu_e$ beam	$\nu_e$ osc	$\bar{\nu}_\mu$ CC	$\bar{\nu}_\mu$ NC	$\bar{\nu}_e$ beam	$\bar{\nu}_e$ osc
beam	14963.3	7283.6	185.3		482.9	363.8	20.0	
beam osc	2489.9	7283.6	185.3	314.8	221.3	363.8	20.0	6.5
reconstructed	2361.5	4346.1	163.6	280.3	213.6	223.8	17.5	5.7
containment	1634.4	3549.2	123.8	221.3	131.5	174.6	13.2	4.5
event length	868.0	2576.4	112.0	201.2	30.3	133.5	11.9	4.1
total ph	665.6	1219.2	64.9	190.6	17.8	64.0	4.5	3.0
hough planes	616.2	903.7	59.6	174.3	17.0	46.6	4.3	2.9
hough frac	198.6	67.5	23.7	77.3	6.8	3.3	2.2	1.6
hough hits/pl	13.1	41.8	22.7	74.4	0.2	2.5	2.1	1.5
beam angle	3.4	34.6	21.9	71.3	0.1	2.0	2.1	1.5
likelihood	1.1	9.7	11.7	56.8	0.0	0.8	1.0	0.9
error	0.2	1.0	0.2	1.0	0.0	0.0	0.0	0.0
raw events	72.0	677.0	4691.0	4809.0	40.0	1039.0	5921.0	6015.0

0.00	0.00	1.85	3.92	0.89	0.42	0.33	0.25	0.29	0.23
0.20	0.18	0.19	0.12	0.15	0.17	0.09	0.14	0.11	0.20
0.17	0.19	0.06	0.07	0.07	0.06	0.04	0.04	0.04	0.03

0.00	0.00	0.00	0.00	0.00	0.03	0.21	0.84	1.50	1.91
2.46	2.17	1.78	0.99	0.45	0.16	0.09	0.05	0.03	0.01
0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00





**Figure 8:** Event distributions for the cut process at 12 km off-axis for neutrino beam events. The top 6 plots (previous page) are for the cuts on individual quantities described in the text, taken in sequence. The bottom three plots (this page) are the  $\log_{10}$  of the three ratios produced by the likelihood analysis. Events which lie in the regions NOT included by the arrows are rejected as  $\nu_e$  candidates. The black curve is for muon CC events, the red curve NC events, green curve beam electron CC events and the blue curve oscillated electron CC events.

## Anti neutrino

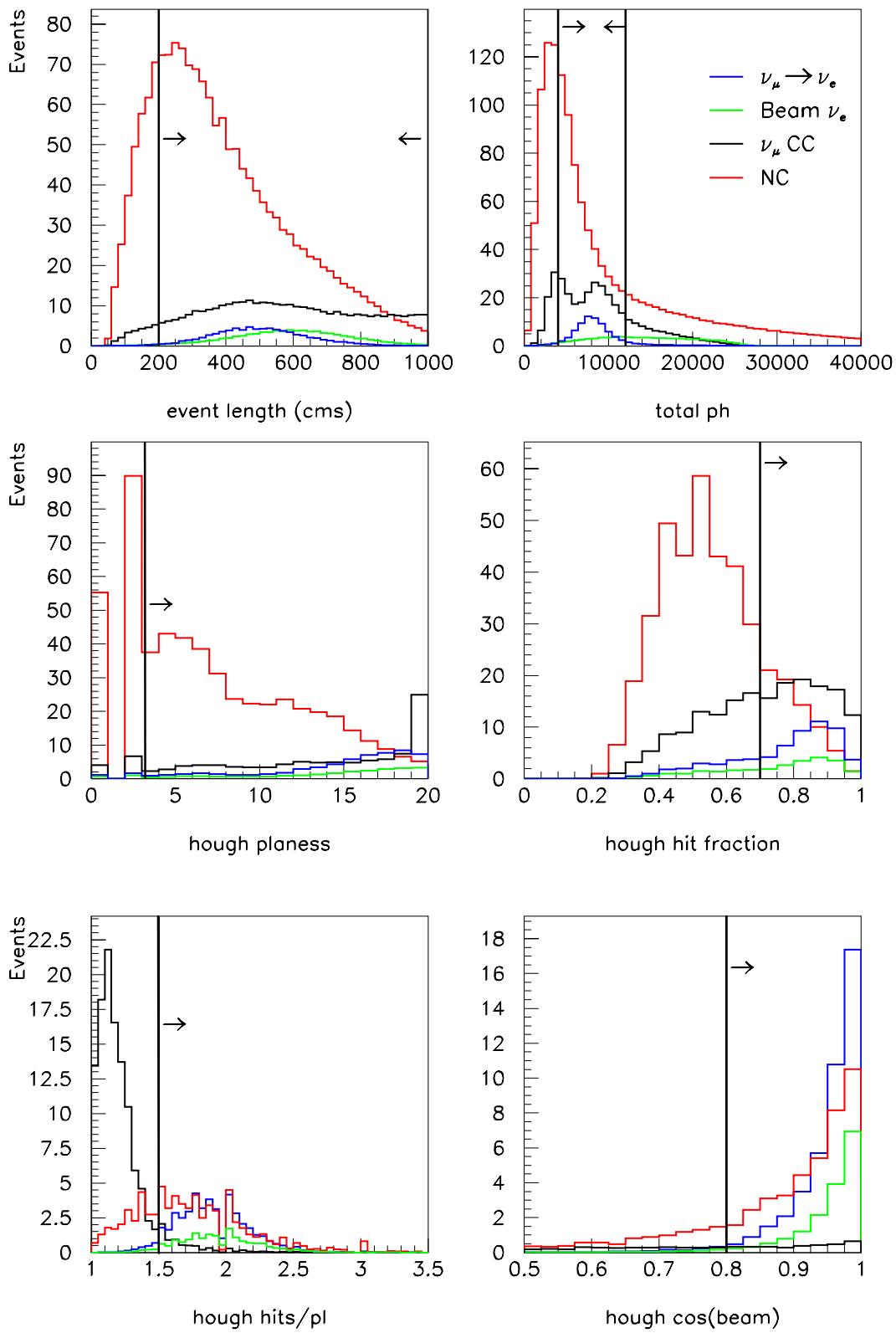
Test	$\nu_\mu$ CC	$\nu_\mu$ NC	$\nu_e$ beam	$\nu_{e\text{osc}}$	$\bar{\nu}_\mu$ CC	$\bar{\nu}_\mu$ NC	$\bar{\nu}_e$ beam	$\bar{\nu}_{e\text{osc}}$
beam	1320.2	987.3	44.9	1311.1	5000.3	2948.5	87.6	5044.7
beam osc	592.8	987.3	44.9	18.1	939.0	2948.5	87.6	102.7
reconstructed	560.4	673.3	39.6	16.0	906.1	1556.4	76.8	89.7
containment	359.7	511.9	29.7	12.5	593.3	1264.6	58.5	71.5
event length	147.8	399.2	26.7	11.2	195.3	911.9	53.0	66.0
total ph	64.4	165.8	9.6	7.5	143.0	377.1	19.0	60.1
hough planes	59.0	120.6	8.7	6.9	137.6	276.6	18.3	57.9
hough fr	29.6	17.9	4.8	4.0	85.9	54.2	12.8	42.4
hough hits/pl	4.0	12.7	4.5	3.8	3.2	39.0	12.3	40.6
beam angle	1.2	9.6	4.1	3.4	1.8	29.0	12.0	39.7
likelihood	0.3	3.4	2.5	2.2	0.5	8.9	8.1	32.1
error	0.0	0.1	0.0	0.0	0.1	0.5	0.1	0.4
raw events	181.0	1403.0	5894.0	6001.0	81.0	1900.0	7752.0	7805.0

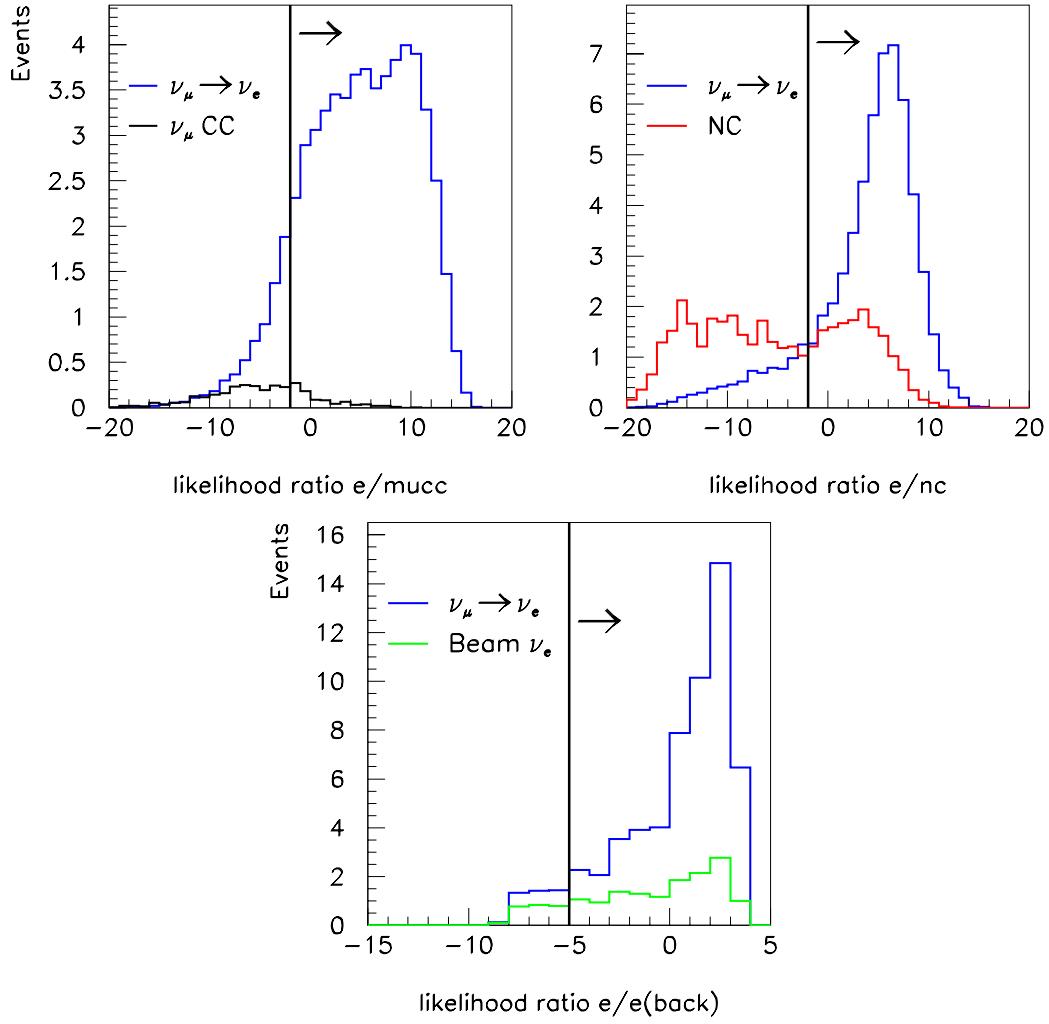
0.00 0.00 0.00 0.00 0.00 0.01 0.00 0.00 0.01 0.05  
 0.17 0.15 0.07 0.07 0.04 0.03 0.02 0.01 0.02 0.01  
 0.02 0.02 0.00 0.01 0.00 0.00 0.01 0.01 0.00 0.00

0.00 0.00 1.58 2.32 1.09 0.68 0.57 0.45 0.42 0.36  
 0.36 0.33 0.35 0.39 0.37 0.31 0.27 0.39 0.35 0.28  
 0.34 0.22 0.17 0.13 0.14 0.10 0.10 0.09 0.08 0.07

0.00 0.00 0.00 0.00 0.00 0.01 0.15 0.59 1.16 1.54  
 1.93 1.75 1.51 0.94 0.53 0.20 0.09 0.05 0.04 0.02  
 0.01 0.01 0.01 0.01 0.00 0.01 0.01 0.01 0.01 0.00

0.00 0.00 0.00 0.00 0.00 0.02 0.24 1.63 5.79 10.26  
 9.24 4.50 1.73 0.64 0.19 0.06 0.02 0.01 0.00 0.00  
 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00





**Figure 9:** Event distributions for the cut process at 12 km off-axis for anti-neutrino beam events. The top 6 plots (previous page) are for the cuts on individual quantities described in the text, taken in sequence. The bottom three plots (this page) are the  $\log_{10}$  of the three ratios produced by the likelihood analysis. Events which lie in the regions NOT included by the arrows are rejected as  $\nu_e$  candidates. The black curve is for muon CC events, the red curve NC events, green curve beam electron CC events and the blue curve oscillated electron CC events.

**14km Off-axis,  $\Delta m^2=0.0025$  eV $^2$**

	$\mu$ CC	NC	e CC	Signal	Back	FOM1	FOM2	Eff.
<b>neutrino</b>	<b>0.5</b>	<b>7.2</b>	<b>9.9</b>	<b>39.2±0.7</b>	<b>17.6±0.5</b>	<b>9.4±0.2</b>	<b>5.2</b>	<b>0.18</b>
<b>Anti-neutrino</b>	<b>0.3</b>	<b>6.7</b>	<b>6.9</b>	<b>19.2±0.3</b>	<b>13.9±0.2</b>	<b>5.1±0.1</b>	<b>3.3</b>	<b>0.20</b>

## Neutrino

Test	$\nu_\mu$ CC	$\nu_\mu$ NC	$\nu_e$ beam	$\nu_{e\text{osc}}$	$\bar{\nu}_\mu$ CC	$\bar{\nu}_\mu$ NC	$\bar{\nu}_e$ beam	$\bar{\nu}_{e\text{osc}}$
beam	10211.4	5215.2	156.4		406.8	304.9	19.0	
beam osc	1558.6	5215.2	156.4	218.9	182.8	304.9	19.0	5.6
reconstructed	1462.6	2996.4	138.0	195.6	176.3	184.7	16.7	4.9
containment	1037.5	2441.3	104.7	157.0	109.1	144.8	12.6	3.8
event length	588.8	1747.5	94.2	140.6	26.8	110.4	11.4	3.5
total ph	392.7	730.4	52.4	130.7	15.4	53.1	4.4	2.6
hough planes	367.1	541.7	48.1	119.1	14.7	38.7	4.2	2.5
hough frac	173.4	41.7	19.5	54.6	6.4	2.7	2.2	1.4
hough hits/pl	14.0	24.9	18.6	51.4	0.2	2.1	2.1	1.3
beam angle	2.4	19.8	17.8	48.2	0.1	1.7	2.1	1.3
likelihood	0.5	6.4	9.1	38.5	0.0	0.8	0.8	0.7
error	0.1	0.5	0.1	0.7	0.0	0.0	0.0	0.0
raw events	88.0	786.0	4444.0	4625.0	54.0	1125.0	5351.0	5423.0

0.00 0.00 0.00 0.00 0.00 0.06 0.07 0.06 0.00 0.10

0.07 0.08 0.04 0.03 0.01 0.02 0.00 0.00 0.00 0.00

0.01 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00

0.00 0.00 1.41 1.79 0.52 0.33 0.25 0.22 0.25 0.22

0.20 0.17 0.18 0.17 0.20 0.16 0.08 0.17 0.14 0.15

0.12 0.13 0.05 0.05 0.04 0.04 0.03 0.02 0.02 0.02

0.00 0.00 0.00 0.00 0.01 0.13 0.47 1.19 1.84 1.98

1.92 1.15 0.65 0.28 0.12 0.06 0.02 0.02 0.01 0.00

0.00 0.00 0.01 0.01 0.00 0.01 0.00 0.00 0.00 0.00

0.00 0.00 0.00 0.00 0.00 0.17 2.09 8.50 13.70 9.32

3.57 1.28 0.40 0.11 0.03 0.01 0.01 0.00 0.00 0.00

0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00

## Anti-neutrino

Test	$\nu_\mu$ CC	$\nu_\mu$ NC	$\nu_e$ beam	$\nu_e$ osc	$\bar{\nu}_\mu$ CC	$\bar{\nu}_\mu$ NC	$\bar{\nu}_e$ beam	$\bar{\nu}_e$ osc
beam	1129.3	834.5	42.7		3298.7	2179.8	75.1	
Beam osc	495.6	834.5	42.7	15.1	581.0	2179.8	75.1	66.0
Reconstructed	466.0	558.0	37.6	13.4	559.2	1139.9	65.7	57.4
Containment	302.6	427.6	28.3	10.5	366.2	922.5	50.1	46.0
event length	128.4	331.8	25.4	9.4	139.7	666.6	45.4	42.3
total ph	56.5	138.4	9.1	6.5	93.3	258.4	15.7	38.5
hough planes	52.1	100.5	8.3	5.9	90.6	190.0	15.0	37.0
Hough fract	27.3	15.2	4.6	3.5	66.5	38.4	10.5	27.1
hough hits/pl	3.7	10.8	4.3	3.3	2.4	26.5	10.0	25.2
beam angle	1.0	7.9	4.0	3.0	1.1	19.8	9.8	24.3
likelihood	0.1	2.3	1.8	1.6	0.2	4.4	5.0	17.6
error	0.0	0.1	0.0	0.0	0.0	0.2	0.1	0.3
raw events	167.0	1190.0	4650.0	4632.0	94.0	1533.0	5996.0	6134.0

0.00 0.00 0.00 0.00 0.00 0.01 0.02 0.01 0.01 0.02  
 0.06 0.07 0.02 0.03 0.02 0.01 0.00 0.01 0.00 0.00  
 0.01 0.01 0.01 0.01 0.00 0.00 0.01 0.00 0.00 0.00

0.00 0.00 0.45 0.76 0.62 0.44 0.34 0.33 0.30 0.26  
 0.28 0.27 0.27 0.32 0.23 0.25 0.23 0.31 0.26 0.17  
 0.11 0.12 0.09 0.07 0.05 0.06 0.04 0.04 0.03 0.03

0.00 0.00 0.00 0.00 0.00 0.03 0.22 0.63 1.12 1.38  
 1.33 1.02 0.56 0.27 0.12 0.06 0.03 0.02 0.01 0.01  
 0.01 0.01 0.01 0.01 0.01 0.01 0.00 0.01 0.00 0.00

0.00 0.00 0.00 0.00 0.00 0.03 0.58 3.26 6.67 4.96  
 2.27 0.95 0.32 0.09 0.03 0.01 0.00 0.00 0.00 0.00  
 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00

**16km Off-axis,  $\Delta m^2=0.0025$  eV $^2$**

	$\mu$ CC	NC	e CC	Signal	Back	FOM1	FOM2	Eff.
<b>neutrino</b>	<b>0.6</b>	<b>5.2</b>	<b>7.6</b>	<b>23.7±0.4</b>	<b>13.4±0.3</b>	<b>6.5±0.2</b>	<b>3.9</b>	<b>0.16</b>
<b>Anti-neutrino</b>	<b>0.2</b>	<b>5.6</b>	<b>5.8</b>	<b>11.5±0.2</b>	<b>11.6±0.2</b>	<b>3.4±0.1</b>	<b>2.4</b>	<b>0.20</b>

## Neutrino

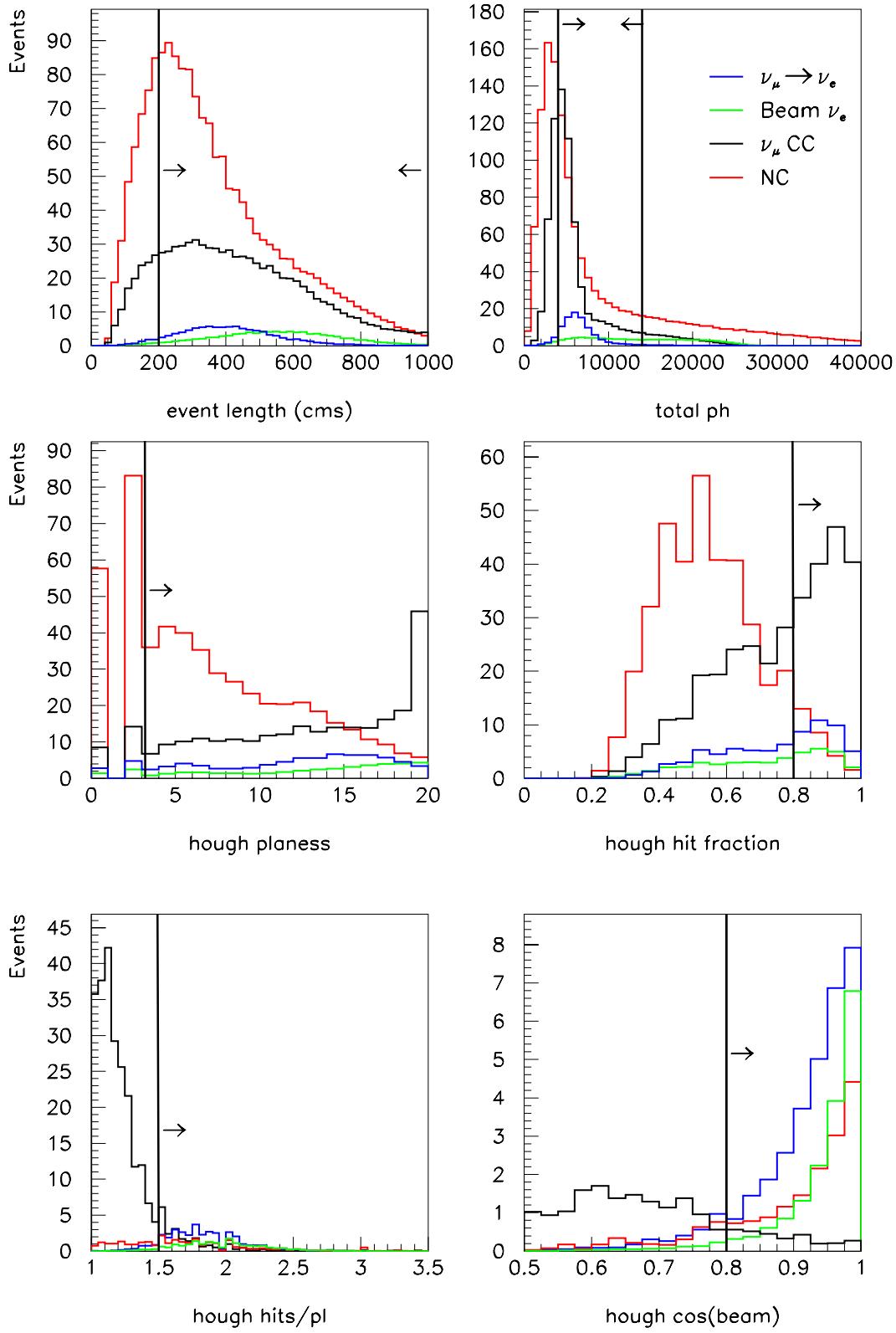
Test	$\nu_\mu$ CC	$\nu_\mu$ NC	$\nu_e$ beam	$\nu_{e\text{osc}}$	$\bar{\nu}_\mu$ CC	$\bar{\nu}_\mu$ NC	$\bar{\nu}_e$ beam	$\bar{\nu}_{e\text{osc}}$
beam	7286.5	3861.0	139.4		345.0	252.1	19.0	
beam osc	1536.9	3861.0	139.4	145.2	154.6	252.1	19.0	4.8
reconstructed	1430.3	2134.9	122.9	129.7	149.0	150.1	16.6	4.2
containment	1063.8	1739.5	93.1	105.4	92.5	118.2	12.6	3.3
event length	669.9	1234.7	83.4	92.5	24.0	89.8	11.4	3.0
total ph	420.5	476.3	43.1	82.6	13.5	43.3	4.3	2.3
hough planes	397.4	350.9	39.4	75.2	13.0	31.5	4.2	2.2
hough fract	238.5	25.5	16.1	35.6	6.0	2.2	2.2	1.2
hough hits/pl	21.5	15.6	15.2	32.7	0.1	1.7	2.1	1.1
beam angle	2.9	12.3	14.4	29.9	0.1	1.4	2.0	1.1
likelihood	0.6	4.5	6.9	23.2	0.0	0.7	0.7	0.6
error	0.1	0.3	0.1	0.4	0.0	0.0	0.0	0.0
raw events	120.0	834.0	4117.0	4294.0	64.0	1156.0	4889.0	4932.0

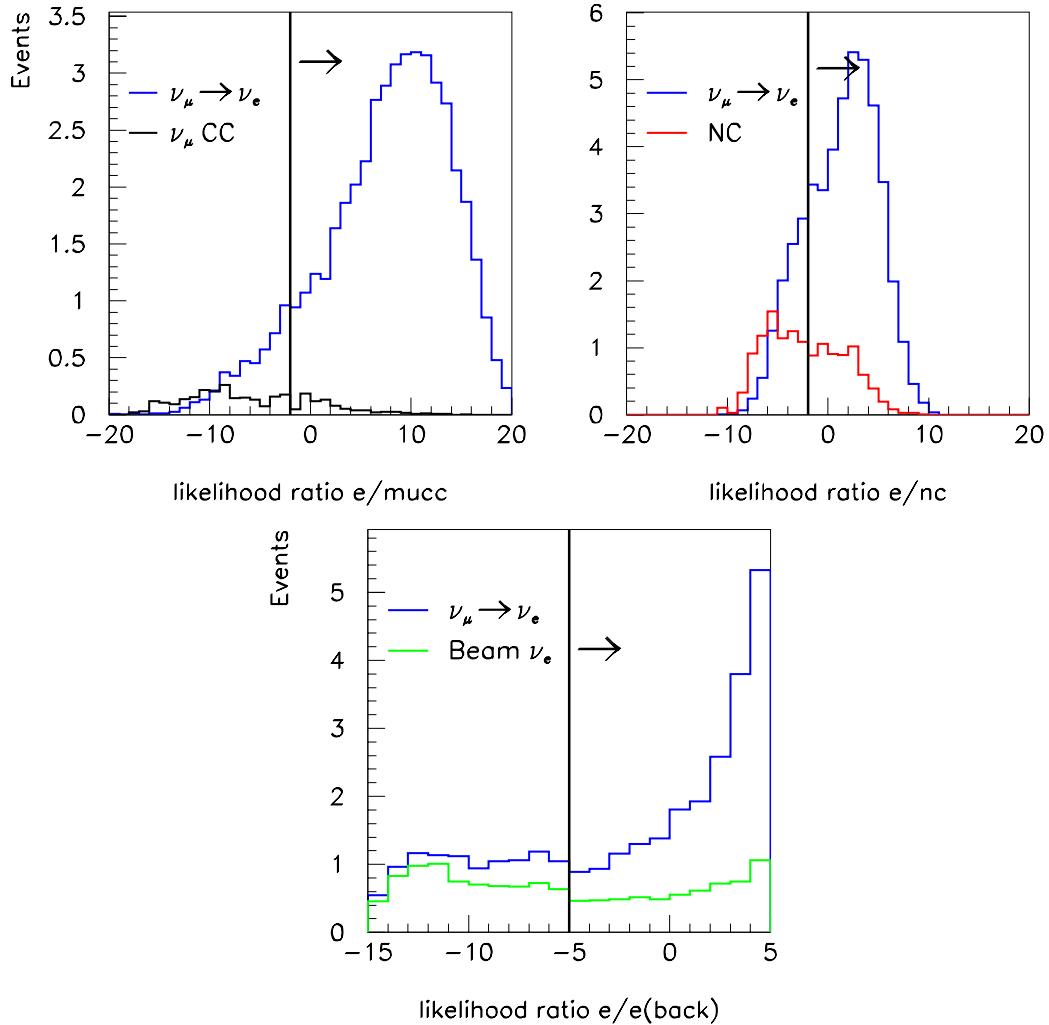
0.00 0.00 0.00 0.00 0.00 0.15 0.24 0.09 0.00 0.04  
0.04 0.03 0.02 0.02 0.00 0.01 0.01 0.00 0.00 0.00  
0.01 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00

0.00 0.00 0.97 0.89 0.39 0.24 0.22 0.22 0.25 0.19  
0.19 0.16 0.21 0.19 0.20 0.18 0.12 0.12 0.08 0.10  
0.07 0.07 0.02 0.02 0.02 0.02 0.01 0.01 0.01 0.01

0.00 0.00 0.00 0.00 0.03 0.21 0.62 1.34 1.64 1.58  
1.18 0.53 0.27 0.09 0.03 0.02 0.01 0.02 0.01 0.00  
0.01 0.00 0.01 0.01 0.01 0.01 0.00 0.00 0.00 0.00

0.00 0.00 0.00 0.00 0.01 0.58 3.99 8.93 5.90 2.75  
1.04 0.36 0.11 0.03 0.01 0.00 0.00 0.00 0.00 0.00  
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00





**Figure 10:** Event distributions for the cut process at 16 km off-axis for neutrino beam events. The top 6 plots (previous page) are for the cuts on individual quantities described in the text, taken in sequence. The bottom three plots (this page) are the  $\log_{10}$  of the three ratios produced by the likelihood analysis. Events which lie in the regions NOT included by the arrows are rejected as  $\nu_e$  candidates. The black curve is for muon CC events, the red curve NC events, green curve beam electron CC events and the blue curve oscillated electron CC events.

## Anti-neutrino

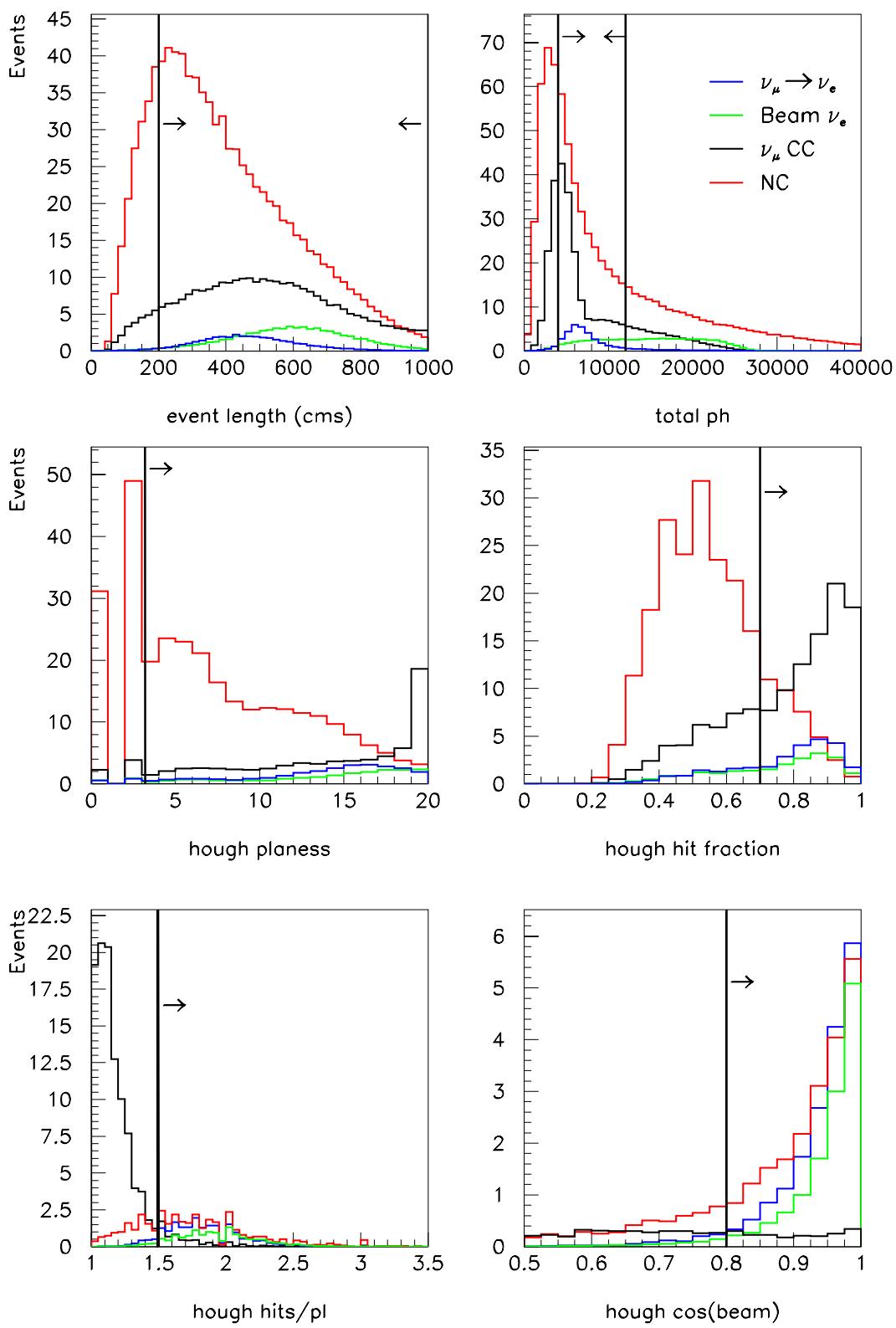
Test	$\nu_\mu$ CC	$\nu_\mu$ NC	$\nu_e$ beam	$\nu_e$ osc	$\bar{\nu}_\mu$ CC	$\bar{\nu}_\mu$ NC	$\bar{\nu}_e$ beam	$\bar{\nu}_e$ osc
beam unosc	984.0	672.5	43.4		2210.6	1603.3	70.2	
beam osc	432.8	672.5	43.4	13.8	507.6	1603.3	70.2	42.8
reconstructed	406.3	440.6	38.2	12.2	486.7	824.8	61.5	37.4
Containment	265.5	340.2	28.7	9.5	326.9	666.6	46.7	30.4
event length	115.3	263.2	25.8	8.5	155.4	483.4	42.2	27.7
total ph	49.9	111.3	9.5	5.9	101.8	186.5	13.4	24.3
hough planes	46.0	81.0	8.6	5.4	99.5	135.8	12.9	23.4
hough fract	25.6	12.2	4.7	3.2	81.6	24.8	9.1	17.4
hough hits/pl	3.5	8.6	4.4	3.0	2.7	18.2	8.6	15.7
beam angle	0.9	6.5	4.1	2.7	1.0	13.3	8.4	15.0
likelihood	0.1	1.9	1.7	1.5	0.1	3.7	4.1	10.1
error	0.0	0.1	0.0	0.0	0.0	0.2	0.1	0.2
raw events	144.0	1112.0	4529.0	4707.0	88.0	1506.0	5996.0	6038.0

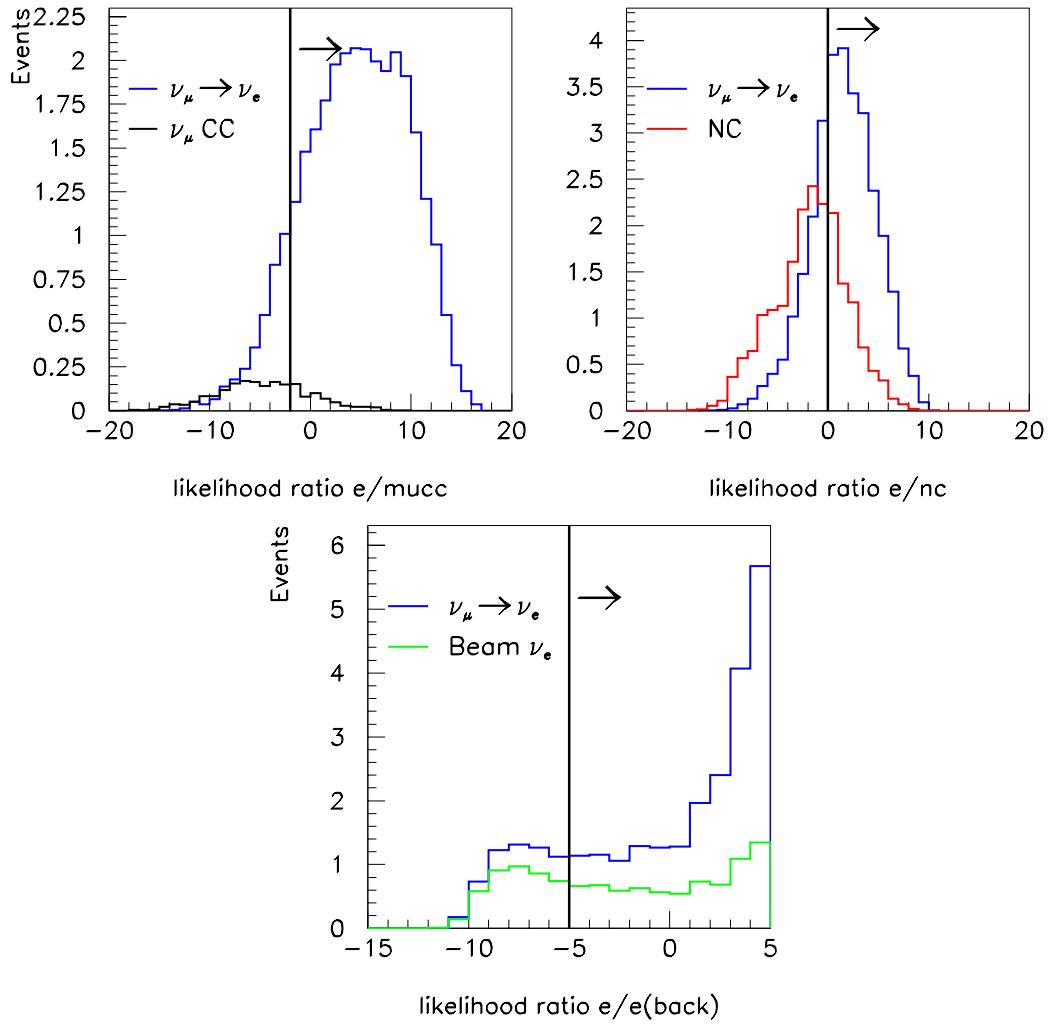
0.00 0.00 0.00 0.00 0.01 0.02 0.01 0.01 0.00 0.01  
 0.03 0.03 0.02 0.01 0.01 0.01 0.00 0.00 0.00 0.00  
 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00

0.00 0.05 0.75 0.59 0.43 0.31 0.29 0.24 0.27 0.24  
 0.22 0.23 0.28 0.23 0.31 0.27 0.15 0.17 0.12 0.08  
 0.09 0.06 0.05 0.03 0.03 0.02 0.02 0.01 0.02 0.01

0.00 0.00 0.00 0.00 0.01 0.09 0.36 0.73 1.17 1.14  
 1.02 0.65 0.32 0.13 0.05 0.03 0.01 0.01 0.02 0.01  
 0.01 0.01 0.01 0.01 0.00 0.01 0.00 0.00 0.01 0.00

0.00 0.00 0.00 0.00 0.00 0.16 1.35 3.82 3.03 1.71  
 0.88 0.38 0.13 0.04 0.01 0.00 0.00 0.00 0.00 0.00  
 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00





**Figure 10:** Event distributions for the cut process at 16 km off-axis for anti-neutrino beam events. The top 6 plots (previous page) are for the cuts on individual quantities described in the text, taken in sequence. The bottom three plots (this page) are the  $\log_{10}$  of the three ratios produced by the likelihood analysis. Events which lie in the regions NOT included by the arrows are rejected as  $\nu_e$  candidates. The black curve is for muon CC events, the red curve NC events, green curve beam electron CC events and the blue curve oscillated electron CC events.

**8km Off-axis,  $\Delta m^2=0.0020$  eV $^2$**

	$\mu$ CC	NC	e CC	Signal	Back	FOM1	FOM2	Eff.
<b>neutrino</b>	<b>4.2</b>	<b>18.7</b>	<b>26.5</b>	<b>68.8±1.0</b>	<b>49.4±2.1</b>	<b>9.8±0.3</b>	<b>6.3</b>	<b>0.16</b>
<b>Anti-neutrino</b>	<b>3.5</b>	<b>19.3</b>	<b>24.6</b>	<b>47.9±0.5</b>	<b>47.4±1.1</b>	<b>7.0±0.1</b>	<b>4.9</b>	<b>0.28</b>

## Neutrino

Test	$\nu_\mu$ CC	$\nu_\mu$ NC	$\nu_e$ beam	$\nu_e$ osc	$\bar{\nu}_\mu$ CC	$\bar{\nu}_\mu$ NC	$\bar{\nu}_e$ beam	$\bar{\nu}_e$ osc
beam	36419.5	16369.9	296.6		747.5	533.4	20.6	
beam osc	19798.5	16369.9	296.6	410.8	467.4	533.4	20.6	7.0
reconstructed	19022.6	10575.3	262.2	364.7	452.2	335.0	18.0	6.1
containment	12522.8	8614.5	195.9	280.3	272.8	261.7	13.7	4.8
event length	5370.6	6538.4	178.4	258.1	49.2	201.3	12.3	4.4
total ph	4691.7	2585.9	100.8	227.1	31.6	74.3	5.4	2.8
ough planes	4292.4	1944.5	93.5	211.8	29.8	54.6	5.3	2.8
ough frac	469.9	80.7	34.8	86.6	5.8	2.7	2.7	1.5
ough hits/pl	20.9	58.6	34.4	85.7	0.1	2.4	2.6	1.5
beam angle	14.6	56.0	34.2	84.9	0.1	2.3	2.6	1.5
likelihood	4.1	17.7	24.7	67.8	0.1	1.0	1.8	1.0
error	0.9	1.9	0.3	0.9	0.0	0.0	0.0	0.0
raw events	35.0	584.0	6150.0	6176.0	29.0	916.0	8539.0	8594.0

0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.04
0.18	0.41	0.18	1.28	0.32	0.55	0.45	0.28	0.25	0.10
0.07	0.00	0.00	0.03	0.00	0.02	0.00	0.00	0.00	

0.00	0.00	0.00	1.52	7.67	3.14	1.11	0.65	0.51	0.40
0.28	0.25	0.32	0.15	0.27	0.28	0.17	0.20	0.20	0.24
0.20	0.21	0.18	0.17	0.16	0.08	0.09	0.12	0.09	0.09

0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.30	0.90
1.67	2.48	3.03	3.29	3.68	3.07	3.20	2.20	1.30	0.67
0.33	0.18	0.09	0.04	0.03	0.04	0.02	0.01	0.00	0.00

0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.09	0.47	2.06
4.68	7.54	10.54	12.80	12.36	9.83	5.43	2.02	0.64	0.22
0.07	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00

## Anti-neutrino

Test	$\nu_\mu$ CC	$\nu_\mu$ NC	$\nu_e$ beam	$\nu_{e\text{osc}}$	$\bar{\nu}_\mu$ CC	$\bar{\nu}_\mu$ NC	$\bar{\nu}_e$ beam	$\bar{\nu}_{e\text{osc}}$
beam	1851.1	1422.8	47.5		13593.0	6243.7	136.2	
beam osc	1095.7	1422.8	47.5	18.9	7564.7	6243.7	136.2	150.4
reconstructed	1044.4	995.6	41.9	16.7	7322.6	3515.2	119.3	132.1
containment	645.6	754.4	31.4	13.0	4724.8	2881.1	90.3	102.2
event length	236.1	594.5	28.3	11.6	1050.0	2110.0	81.8	93.8
total ph	146.5	225.9	13.8	7.2	901.7	683.5	40.7	83.9
hough planes	132.5	167.5	12.8	6.7	856.5	507.6	39.6	81.5
hough fract	32.9	15.2	6.9	3.9	310.6	67.9	27.8	59.1
hough hits/pl	3.7	12.6	6.7	3.8	17.9	57.0	27.5	58.5
beam angle	2.6	11.2	6.6	3.6	14.5	50.3	27.4	58.2
likelihood	0.7	3.9	4.4	2.1	2.8	15.4	20.2	45.8
error	0.1	0.1	0.0	0.0	0.5	0.9	0.2	0.5
raw events	149.0	1167.0	8256.0	8316.0	53.0	1558.0	11460.0	11469.0

0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00  
 0.03 0.03 0.16 0.66 0.52 0.58 0.65 0.29 0.23 0.06  
 0.09 0.06 0.06 0.03 0.02 0.03 0.01 0.03 0.01 0.01

0.00 0.00 0.06 0.79 5.34 3.09 1.29 0.81 0.77 0.58  
 0.48 0.52 0.43 0.40 0.41 0.44 0.31 0.46 0.30 0.35  
 0.37 0.32 0.32 0.22 0.28 0.21 0.21 0.22 0.15 0.12

0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.04 0.24 0.64  
 1.20 1.68 2.30 2.88 3.03 3.10 3.31 2.68 1.70 0.82  
 0.44 0.22 0.11 0.06 0.05 0.03 0.03 0.02 0.01 0.00

0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.05 0.40 1.37  
 3.01 4.89 6.84 8.67 8.85 6.87 4.12 1.83 0.66 0.21  
 0.07 0.03 0.01 0.01 0.00 0.00 0.00 0.00 0.00 0.00

## 10km Off-axis, $\Delta m^2 = 0.0020$ eV $^2$

	$\mu$ CC	NC	e CC	Signal	Back	FOM1	FOM2	Eff.
<b>neutrino</b>	<b>3.2</b>	<b>12.1</b>	<b>16.3</b>	<b>55.5±0.9</b>	<b>31.6±1.4</b>	<b>9.9±0.3</b>	<b>5.9</b>	<b>0.16</b>
<b>Anti-neutrino</b>	<b>1.6</b>	<b>12.2</b>	<b>14.5</b>	<b>36.3±0.4</b>	<b>28.3±0.6</b>	<b>6.8±0.1</b>	<b>4.5</b>	<b>0.27</b>

## Neutrino

Test	$\nu_\mu$ CC	$\nu_\mu$ NC	$\nu_e$ beam	$\nu_e$ osc	$\bar{\nu}_\mu$ CC	$\bar{\nu}_\mu$ NC	$\bar{\nu}_e$ beam	$\bar{\nu}_e$ osc
beam	22858.2	10593.9	229.0		597.5	434.5	20.6	
beam osc	9490.8	10593.9	229.0	334.0	353.7	434.5	20.6	6.1
reconstructed	9089.1	6559.6	202.4	296.7	342.0	269.8	18.0	5.3
containment	6250.1	5369.2	152.4	231.2	209.0	210.7	13.6	4.2
event length	3205.3	3967.3	138.4	211.7	41.1	161.4	12.3	3.8
total ph	2650.0	1176.9	67.7	179.8	23.4	51.4	4.1	2.3
hough planes	2458.9	883.0	62.5	166.9	22.2	37.6	3.9	2.2
hough fract	497.9	44.6	24.0	72.3	5.3	1.9	2.0	1.2
hough hits/pl	17.7	32.5	23.6	71.0	0.1	1.7	2.0	1.2
beam angle	10.2	31.3	23.3	69.8	0.1	1.6	2.0	1.2
likelihood	3.2	11.3	15.0	54.7	0.0	0.8	1.3	0.8
error	0.6	1.3	0.2	0.9	0.0	0.0	0.0	0.0
raw events	43.0	552.0	4760.0	4889.0	22.0	847.0	6332.0	6362.0

0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.16
0.69	0.90	0.19	0.88	0.23	0.07	0.03	0.00	0.02	0.01
0.03	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.00

0.00	0.00	0.09	4.93	2.65	0.68	0.41	0.30	0.24	0.24
0.21	0.16	0.20	0.12	0.13	0.18	0.10	0.16	0.11	0.20
0.16	0.23	0.07	0.12	0.10	0.04	0.06	0.07	0.05	0.04

0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.23	0.82	1.58
2.05	2.56	2.77	2.58	1.94	0.87	0.44	0.16	0.11	0.05
0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00

## Anti-neutrino

Test	$\nu_\mu$ CC	$\nu_\mu$ NC	$\nu_e$ beam	$\nu_e$ osc	$\bar{\nu}_\mu$ CC	$\bar{\nu}_\mu$ NC	$\bar{\nu}_e$ beam	$\bar{\nu}_e$ osc
beam	1561.7	1184.4	46.0		8082.8	4209.8	105.8	
beam osc	877.9	1184.4	46.0	17.1	3516.9	4209.8	105.8	115.1
reconstructed	834.9	819.7	40.5	15.1	3400.2	2271.4	92.7	100.8
containment	523.9	621.0	30.4	11.9	2268.6	1858.5	70.5	79.3
event length	200.1	486.5	27.3	10.5	688.6	1345.1	64.0	73.0
total ph	107.4	157.3	10.5	6.0	572.2	351.3	26.6	63.8
hough planes	97.4	116.2	9.7	5.5	548.4	257.6	25.8	61.8
hough fract	29.3	11.5	5.2	3.2	273.9	35.9	18.2	45.5
hough hits/pl	3.0	9.4	5.1	3.1	10.6	29.8	17.9	44.6
beam angle	2.0	8.3	5.0	3.0	7.9	25.9	17.7	44.2
likelihood	0.5	3.1	3.0	1.8	1.1	9.1	11.5	34.5
error	0.0	0.1	0.0	0.0	0.2	0.6	0.1	0.4
raw events	143.0	1097.0	6384.0	6516.0	45.0	1492.0	8667.0	8756.0

0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.04  
 0.21 0.10 0.16 0.41 0.27 0.11 0.06 0.05 0.04 0.02  
 0.04 0.01 0.01 0.01 0.01 0.02 0.01 0.00 0.01 0.00

0.00 0.00 0.31 2.43 1.86 0.90 0.65 0.50 0.44 0.36  
 0.33 0.34 0.28 0.34 0.30 0.29 0.26 0.34 0.29 0.24  
 0.34 0.28 0.24 0.19 0.18 0.10 0.12 0.13 0.10 0.08

0.00 0.00 0.00 0.00 0.00 0.00 0.02 0.17 0.63 1.15  
 1.53 1.95 2.36 2.22 2.04 1.14 0.61 0.36 0.13 0.07  
 0.04 0.03 0.02 0.02 0.01 0.01 0.01 0.01 0.01 0.00

0.00 0.00 0.00 0.00 0.00 0.00 0.03 0.32 1.34 3.71  
 7.54 9.54 7.44 4.02 1.59 0.52 0.16 0.05 0.02 0.01  
 0.01 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00

**12km Off-axis,  $\Delta m^2=0.0020$  eV $^2$**

	$\mu$ CC	NC	e CC	Signal	Back	FOM1	FOM2	Eff.
<b>neutrino</b>	<b>2.4</b>	<b>10.4</b>	<b>12.4</b>	<b>46.9±0.8</b>	<b>25.2±1.1</b>	<b>9.3±0.3</b>	<b>5.5</b>	<b>0.17</b>
<b>anti-neutrino</b>	<b>1.0</b>	<b>10.0</b>	<b>9.5</b>	<b>25.7±0.3</b>	<b>20.5±0.5</b>	<b>5.7±0.1</b>	<b>3.8</b>	<b>0.26</b>

## Neutrino

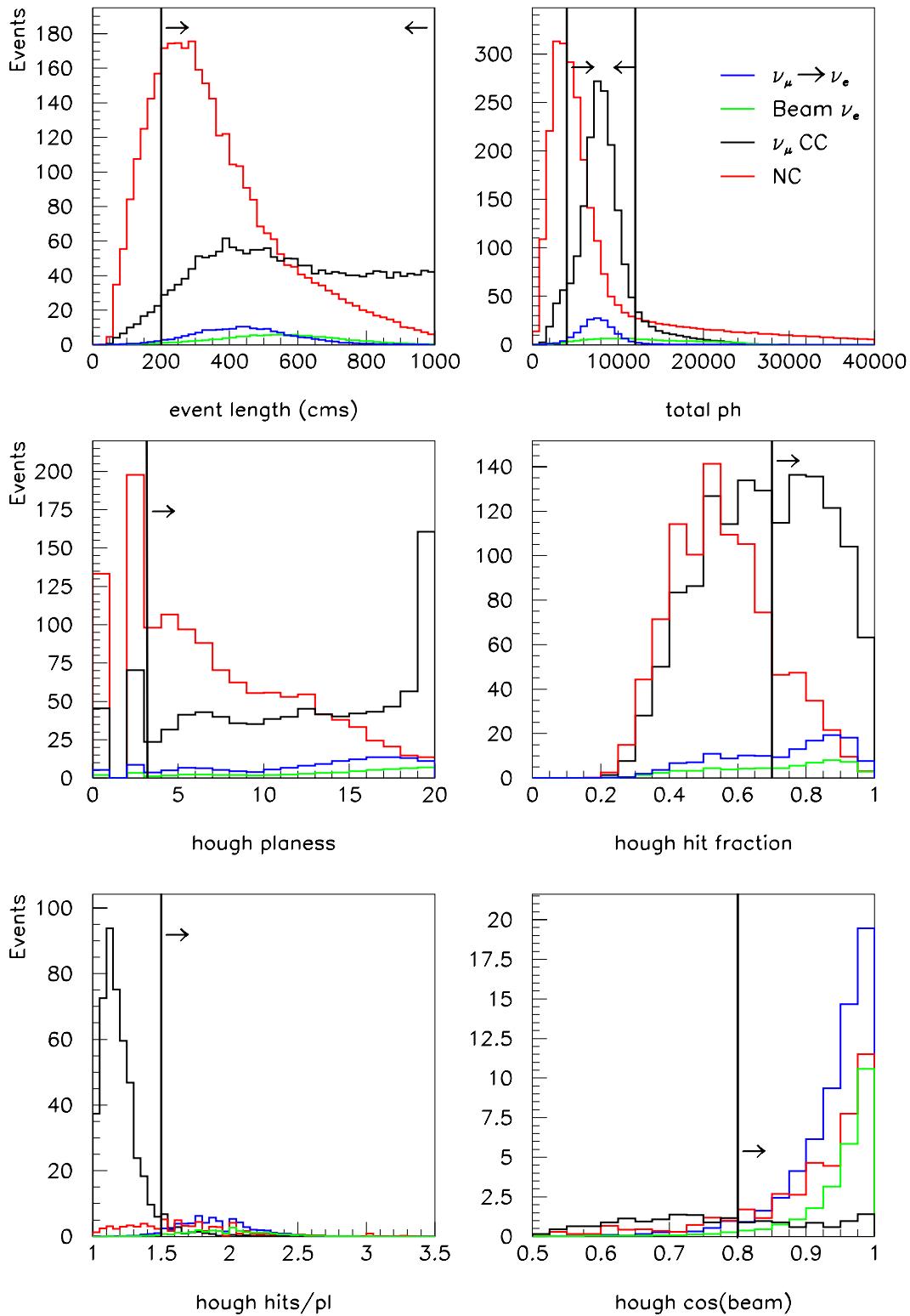
Test	$\nu_\mu$ CC	$\nu_\mu$ NC	$\nu_e$ beam	$\nu_e$ osc	$\bar{\nu}_\mu$ CC	$\bar{\nu}_\mu$ NC	$\bar{\nu}_e$ beam	$\bar{\nu}_e$ osc
beam	14963.3	7283.6	185.3		482.9	363.8	20.0	
beam osc	4508.6	7283.6	185.3	264.1	271.9	363.8	20.0	5.3
reconstructed	4299.4	4346.1	163.6	235.3	262.7	223.8	17.5	4.6
containment	3016.8	3549.2	123.8	186.5	161.9	174.6	13.2	3.6
event length	1736.2	2576.4	112.0	168.8	34.4	133.5	11.9	3.3
total ph	1532.9	1219.2	64.9	159.2	22.6	64.0	4.5	2.5
hough planes	1419.5	903.7	59.6	145.5	21.5	46.6	4.3	2.4
hough fract	448.9	67.5	23.7	65.0	6.3	3.3	2.2	1.3
hough hits/pl	19.7	41.8	22.7	62.3	0.1	2.5	2.1	1.3
beam angle	7.4	34.6	21.9	59.4	0.1	2.0	2.1	1.2
likelihood	2.4	9.6	11.4	46.2	0.0	0.8	1.0	0.7
error	0.4	1.0	0.2	0.8	0.0	0.0	0.0	0.0
raw events	62.0	679.0	4621.0	4755.0	35.0	1015.0	5811.0	5914.0

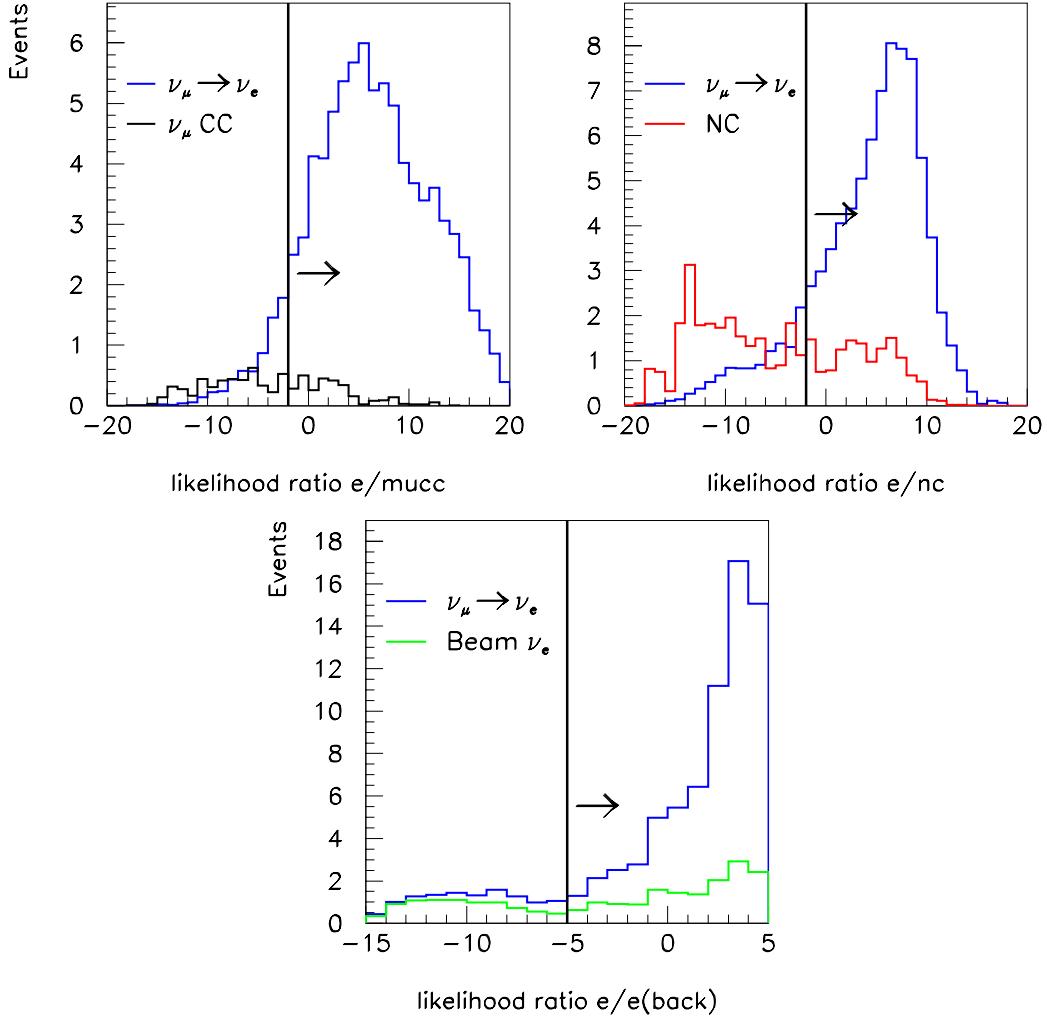
0.00 0.00 0.00 0.00 0.00 0.00 0.03 0.07 0.73  
 0.58 0.59 0.14 0.16 0.05 0.04 0.00 0.00 0.01 0.01  
 0.01 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00

0.00 0.00 1.66 4.05 0.94 0.41 0.34 0.24 0.29 0.22  
 0.20 0.18 0.17 0.12 0.15 0.17 0.09 0.14 0.13 0.18  
 0.17 0.19 0.06 0.06 0.07 0.06 0.04 0.04 0.04 0.03

0.00 0.00 0.00 0.00 0.00 0.04 0.24 0.91 1.51 1.85  
 2.39 2.09 1.70 0.90 0.42 0.14 0.08 0.04 0.03 0.01  
 0.00 0.01 0.01 0.01 0.01 0.01 0.01 0.00 0.00 0.00

0.00 0.00 0.00 0.00 0.00 0.06 0.54 2.98 9.30 15.39  
 11.53 4.86 1.62 0.45 0.12 0.03 0.01 0.00 0.00 0.00  
 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00





**Figure 11:** Event distributions for the cut process at 12 km off-axis for neutrino beam events with  $\Delta m^2=0.0020\text{ eV}^2$ . The top 6 plots (previous page) are for the cuts on individual quantities described in the text, taken in sequence. The bottom three plots (this page) are the  $\log_{10}$  of the three ratios produced by the likelihood analysis. Events which lie in the regions NOT included by the arrows are rejected as  $\nu_e$  candidates. The black curve is for muon CC events, the red curve NC events, green curve beam electron CC events and the blue curve oscillated electron CC events.

## Anti-neutrino

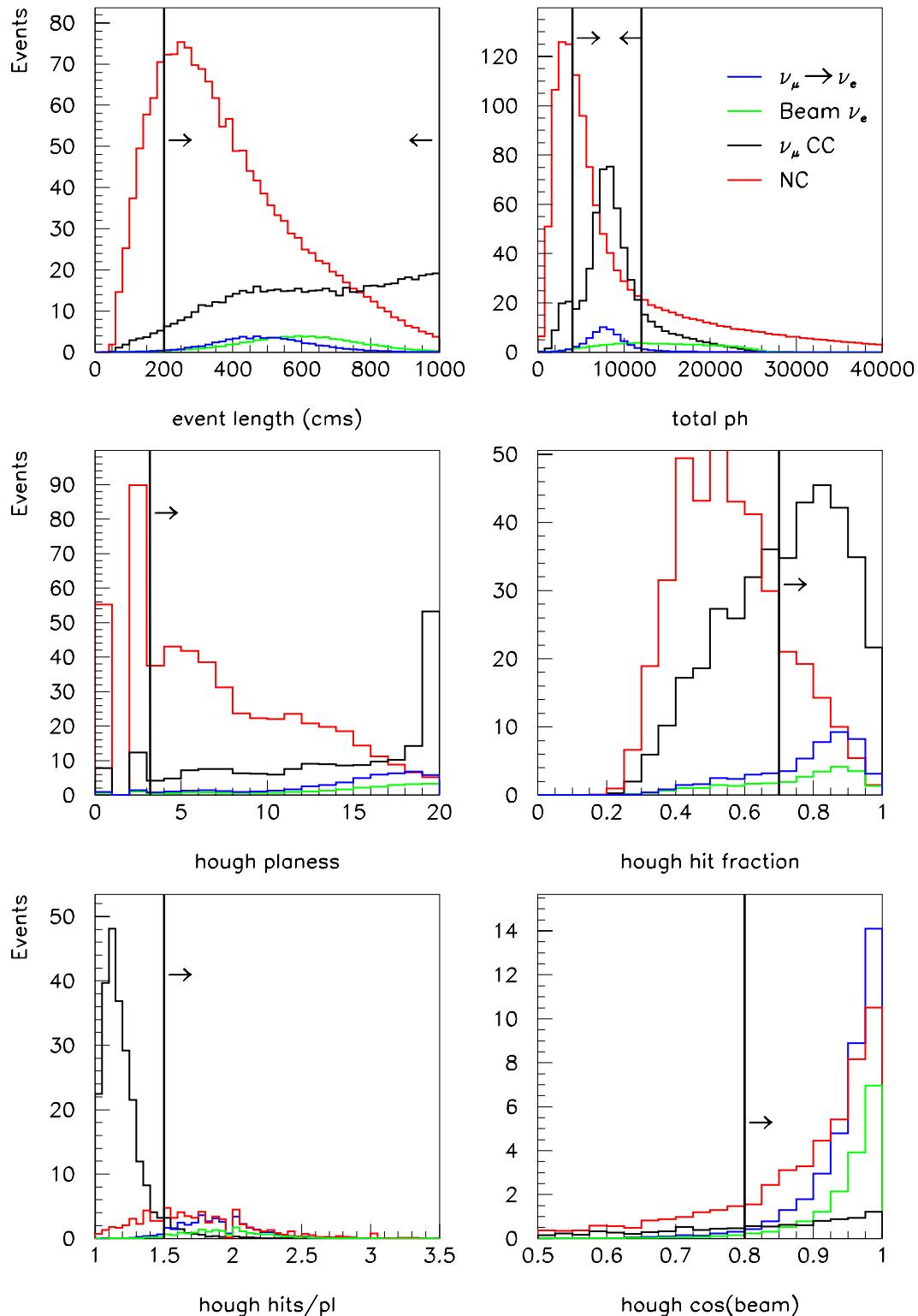
Test	$\nu_\mu$ CC	$\nu_\mu$ NC	$\nu_e$ beam	$\nu_e$ osc	$\bar{\nu}_\mu$ CC	$\bar{\nu}_\mu$ NC	$\bar{\nu}_e$ beam	$\bar{\nu}_e$ osc
beam	1320.2	987.3	44.9		5000.3	2948.5	87.6	
beam osc	702.7	987.3	44.9	15.5	1658.0	2948.5	87.6	84.5
reconstructed	666.2	673.3	39.6	13.7	1601.2	1556.4	76.8	73.8
containment	422.7	511.9	29.7	10.8	1076.8	1264.6	58.5	59.0
event length	167.6	399.2	26.7	9.5	398.8	911.9	53.0	54.5
total ph	83.1	165.8	9.6	6.7	338.9	377.1	19.0	49.9
hough planes	75.6	120.6	8.7	6.1	326.5	276.6	18.3	48.0
hough fract	30.6	17.9	4.8	3.6	203.4	54.2	12.8	35.2
hough hits/pl	3.4	12.7	4.5	3.4	7.1	39.0	12.3	33.5
beam angle	1.6	9.6	4.1	3.0	4.3	29.0	12.0	32.7
likelihood	0.3	2.7	2.2	1.6	0.7	7.3	7.3	24.0
error	0.0	0.1	0.0	0.0	0.1	0.4	0.1	0.3
raw events	142.0	1116.0	5199.0	5323.0	52.0	1586.0	6895.0	6948.0

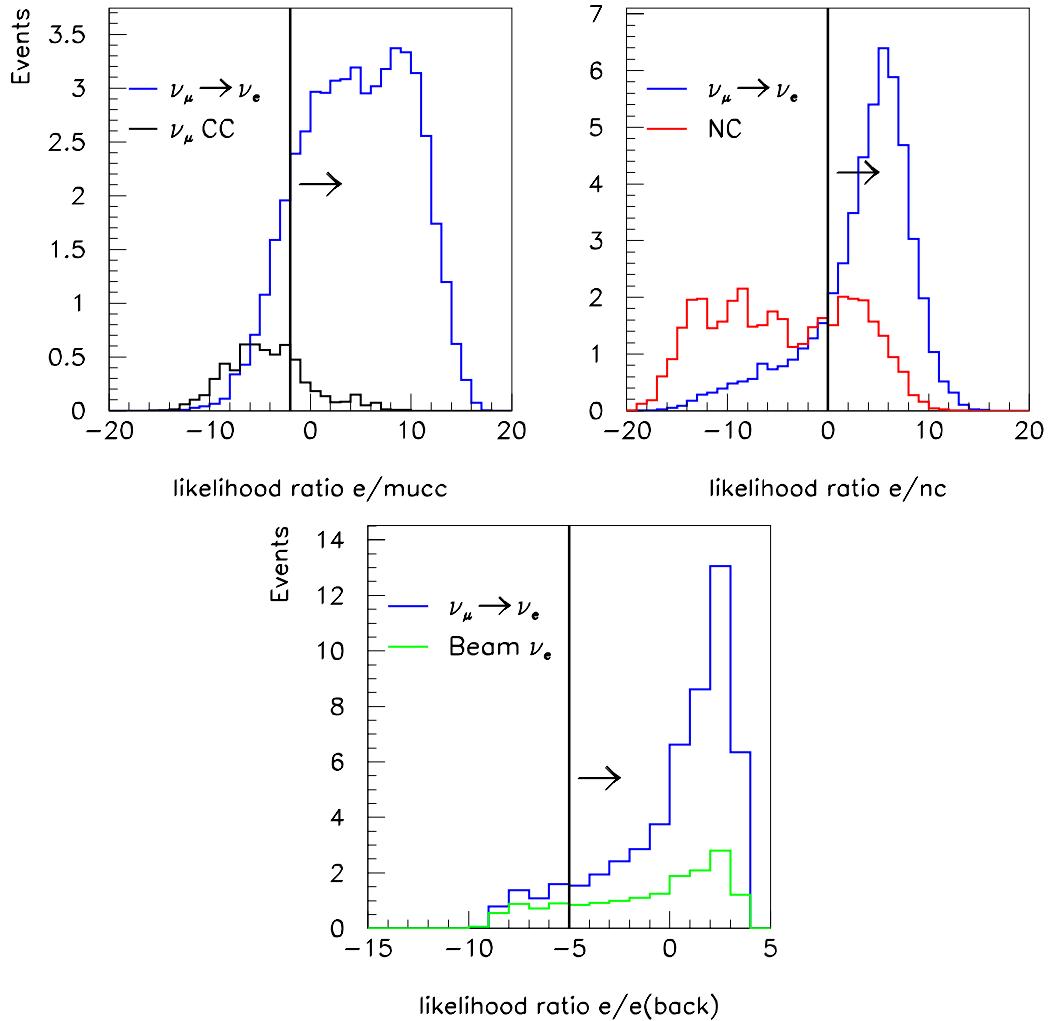
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.07 0.18  
 0.27 0.14 0.10 0.08 0.05 0.03 0.01 0.01 0.01  
 0.02 0.01 0.00 0.01 0.00 0.00 0.01 0.00 0.00

0.00 0.00 1.32 1.75 0.87 0.56 0.46 0.37 0.35 0.30  
 0.29 0.29 0.29 0.32 0.29 0.25 0.23 0.32 0.30 0.25  
 0.28 0.19 0.13 0.11 0.12 0.08 0.07 0.07 0.07 0.05

0.00 0.00 0.00 0.00 0.00 0.01 0.10 0.46 1.03 1.44  
 1.85 1.65 1.33 0.78 0.43 0.15 0.08 0.04 0.03 0.01  
 0.01 0.01 0.01 0.01 0.00 0.01 0.01 0.01 0.01 0.00

0.00 0.00 0.00 0.00 0.00 0.01 0.20 1.28 4.55 7.91  
 6.87 3.20 1.08 0.37 0.11 0.04 0.01 0.00 0.00 0.00  
 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00





**Figure 12** Event distributions for the cut process at 12 km off-axis for anti-neutrino beam events with  $\Delta m^2 = 0.0020 \text{ eV}^2$ . The top 6 plots (previous page) are for the cuts on individual quantities described in the text, taken in sequence. The bottom three plots (this page) are the  $\log_{10}$  of the three ratios produced by the likelihood analysis. Events which lie in the regions NOT included by the arrows are rejected as  $\nu_e$  candidates. The black curve is for muon CC events, the red curve NC events, green curve beam electron CC events and the blue curve oscillated electron CC events.

**14km Off-axis,  $\Delta m^2=0.0020$  eV $^2$**

	$\mu$ CC	NC	e CC	Signal	Back	FOM1	FOM2	Eff.
<b>neutrino</b>	<b>1.0</b>	<b>6.9</b>	<b>9.3</b>	<b>34.7±0.6</b>	<b>17.2±0.6</b>	<b>8.4±0.2</b>	<b>4.8</b>	<b>0.17</b>
<b>anti-neutrino</b>	<b>0.6</b>	<b>7.2</b>	<b>6.4</b>	<b>16.5±0.3</b>	<b>14.2±0.3</b>	<b>4.4±0.1</b>	<b>3.0</b>	<b>0.22</b>

## Neutrino

Test	$\nu_\mu$ CC	$\nu_\mu$ NC	$\nu_e$ beam	$\nu_e$ osc	$\bar{\nu}_\mu$ CC	$\bar{\nu}_\mu$ NC	$\bar{\nu}_e$ beam	$\bar{\nu}_e$ osc
beam	10211.4	5215.2	156.4		406.8	304.9	19.0	
beam osc	2274.2	5215.2	156.4	200.9	223.0	304.9	19.0	4.6
reconstructed	2152.2	2996.4	138.0	179.6	215.3	184.7	16.7	4.0
containment	1511.1	2441.3	104.7	144.9	133.1	144.8	12.6	3.2
event length	881.6	1747.5	94.2	128.9	29.4	110.4	11.4	2.9
total ph	721.2	730.4	52.4	118.8	19.0	53.1	4.4	2.2
ough planes	670.0	541.7	48.1	108.2	18.1	38.7	4.2	2.2
ough fract	257.2	41.7	19.5	50.2	5.6	2.7	2.2	1.2
ough hits/pl	12.5	24.9	18.6	46.9	0.1	2.1	2.1	1.1
beam angle	3.7	19.8	17.8	43.6	0.1	1.7	2.1	1.1
likelihoold	1.0	6.2	8.5	34.1	0.0	0.7	0.8	0.6
error	0.1	0.5	0.1	0.6	0.0	0.0	0.0	0.0
raw events	69.0	740.0	4198.0	4390.0	38.0	1065.0	5017.0	5056.0

0.00 0.00 0.00 0.00 0.00 0.01 0.00 0.13 0.11 0.35

0.17 0.13 0.04 0.02 0.00 0.02 0.00 0.00 0.00 0.00

0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00

0.00 0.00 1.63 1.60 0.50 0.31 0.25 0.20 0.24 0.20

0.18 0.17 0.19 0.16 0.18 0.16 0.08 0.17 0.13 0.15

0.11 0.13 0.05 0.04 0.03 0.03 0.02 0.02 0.02 0.02

0.00 0.00 0.00 0.00 0.02 0.16 0.53 1.24 1.83 1.87

1.73 0.95 0.51 0.21 0.07 0.04 0.02 0.01 0.01 0.00

0.00 0.00 0.01 0.01 0.00 0.01 0.00 0.00 0.00 0.00

0.00 0.00 0.00 0.00 0.02 0.34 2.66 8.66 12.02 7.34

2.53 0.80 0.22 0.06 0.02 0.01 0.00 0.00 0.00 0.00

0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00

## Anti-neutrino

Test	$\nu_\mu$ CC	$\nu_\mu$ NC	$\nu_e$ beam	$\nu_e$ osc	$\bar{\nu}_\mu$ CC	$\bar{\nu}_\mu$ NC	$\bar{\nu}_e$ beam	$\bar{\nu}_e$ osc
beam	1129.3	810.4	44.3		3239.6	2144.9	76.0	
beam osc	581.0	810.4	44.3	13.7	861.5	2144.9	76.0	59.9
reconstructed	548.9	542.0	39.0	12.1	830.8	1117.9	66.5	52.3
containment	350.3	415.3	29.3	9.6	550.9	903.4	50.6	42.3
event length	141.8	322.7	26.3	8.5	212.8	653.0	45.8	38.8
total ph	70.6	134.9	9.5	6.1	170.7	256.5	16.0	35.4
hough planes	64.3	98.2	8.6	5.5	165.1	187.7	15.4	34.0
hough fract	27.0	14.7	4.7	3.3	112.6	35.6	10.9	25.1
hough hits/pl	3.0	10.4	4.4	3.1	3.6	26.1	10.3	23.2
beam angle	1.4	7.8	4.0	2.7	2.0	19.2	10.1	22.4
likelihood	0.2	2.1	1.7	1.4	0.4	5.1	4.7	15.1
error	0.0	0.1	0.0	0.0	0.1	0.3	0.1	0.2
raw events	122.0	1037.0	4385.0	4500.0	59.0	1448.0	5710.0	5734.0

0.00 0.00 0.00 0.00 0.00 0.00 0.02 0.09 0.13  
 0.10 0.09 0.03 0.02 0.02 0.01 0.00 0.00 0.00  
 0.00 0.01 0.00 0.00 0.00 0.00 0.00 0.00 0.00

0.00 0.00 1.31 0.86 0.56 0.35 0.34 0.27 0.28 0.24  
 0.24 0.22 0.27 0.24 0.29 0.24 0.17 0.25 0.26 0.14  
 0.14 0.11 0.09 0.06 0.06 0.04 0.04 0.03 0.03 0.02

0.00 0.00 0.00 0.00 0.00 0.03 0.24 0.68 1.18 1.34  
 1.23 0.83 0.46 0.20 0.07 0.04 0.02 0.01 0.02 0.01  
 0.01 0.01 0.01 0.01 0.00 0.01 0.00 0.00 0.01 0.00

0.00 0.00 0.00 0.00 0.00 0.07 0.77 3.46 5.66 3.95  
 1.70 0.58 0.18 0.05 0.02 0.00 0.00 0.00 0.00 0.00  
 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00

**10km Off-axis,  $\Delta m^2 = 0.0015 \text{ eV}^2$**

	$\mu$ CC	NC	e CC	Signal	Back	FOM1	FOM2	Eff.
<b>neutrino</b>	<b>5.6</b>	<b>12.1</b>	<b>16.3</b>	<b>35.6±0.6</b>	<b>34.0±1.7</b>	<b>6.1±0.2</b>	<b>4.3</b>	<b>0.16</b>
<b>anti-neutrino</b>	<b>2.4</b>	<b>12.6</b>	<b>14.4</b>	<b>23.3±0.3</b>	<b>29.4±0.7</b>	<b>4.3±0.1</b>	<b>3.2</b>	<b>0.26</b>

# Neutrino

Test	$\nu_\mu$ CC	$\nu_\mu$ NC	$\nu_e$ beam	$\nu_{e\text{osc}}$	$\bar{\nu}_\mu$ CC	$\bar{\nu}_\mu$ NC	$\bar{\nu}_e$ beam	$\bar{\nu}_{e\text{osc}}$
beam	22858.2	10593.9	229.0		597.5	434.5	20.6	
beam osc	13951.4	10593.9	229.0	222.6	428.7	434.5	20.6	4.2
reconstructed	13378.5	6559.6	202.4	197.6	414.7	269.8	18.0	3.7
containment	9298.2	5369.2	152.4	154.7	256.5	210.7	13.6	2.9
event length	4998.5	3967.3	138.4	140.7	55.8	161.4	12.3	2.6
total ph	4186.5	1176.9	67.7	116.1	37.0	51.4	4.1	1.5
hough planes	3895.9	883.0	62.5	107.8	35.3	37.6	3.9	1.4
hough fract	901.0	44.6	24.0	46.9	10.9	1.9	2.0	0.8
hough hits/pl	30.9	32.5	23.6	46.0	0.2	1.7	2.0	0.8
beam angle	16.7	31.3	23.3	45.2	0.1	1.6	2.0	0.8
likelihood	5.6	11.3	15.0	35.2	0.0	0.8	1.3	0.5
error	1.0	1.3	0.2	0.6	0.0	0.0	0.0	0.0
raw events	47.0	556.0	4763.0	4875.0	22.0	845.0	6333.0	6370.0

0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.04	0.33
1.20	1.66	0.49	1.18	0.39	0.08	0.06	0.00	0.02	0.02
0.04	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.00

0.00	0.00	0.09	4.93	2.66	0.70	0.41	0.31	0.25	0.24
0.21	0.16	0.20	0.13	0.13	0.18	0.10	0.16	0.12	0.20
0.16	0.23	0.08	0.12	0.10	0.04	0.06	0.06	0.05	0.04

0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.25	0.86	1.61
2.07	2.56	2.77	2.56	1.87	0.81	0.41	0.16	0.11	0.05
0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00

## Anti-neutrino

Test	$\nu_\mu$ CC	$\nu_\mu$ NC	$\nu_e$ beam	$\nu_e$ osc	$\bar{\nu}_\mu$ CC	$\bar{\nu}_\mu$ NC	$\bar{\nu}_e$ beam	$\bar{\nu}_e$ osc
beam	1561.7	1184.4	46.0		8082.8	4209.8	105.8	
beam osc	1054.2	1184.4	46.0	12.7	5095.4	4209.8	105.8	75.4
reconstructed	1006.7	819.7	40.5	11.2	4925.9	2271.4	92.7	66.0
containment	636.5	621.0	30.4	8.9	3324.3	1858.5	70.5	52.0
event length	258.2	486.5	27.3	7.7	1097.1	1345.1	64.0	47.9
total ph	159.1	157.3	10.5	3.9	927.7	351.3	26.6	41.1
hough planes	145.7	116.2	9.7	3.6	891.7	257.6	25.8	39.8
hough frac	52.8	11.5	5.2	2.2	474.5	35.9	18.2	29.3
hough hits/pl	4.8	9.4	5.1	2.1	17.1	29.8	17.9	28.8
beam angle	2.9	8.3	5.0	2.0	12.4	25.9	17.7	28.5
likelihood	0.7	3.2	3.0	1.2	1.7	9.4	11.4	22.1
error	0.1	0.1	0.0	0.0	0.3	0.6	0.1	0.3
raw events	145.0	1120.0	6369.0	6509.0	49.0	1520.0	8649.0	8707.0

0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.01 0.01 0.08  
 0.37 0.16 0.32 0.56 0.36 0.13 0.08 0.06 0.05 0.03  
 0.05 0.02 0.01 0.01 0.01 0.02 0.01 0.00 0.01 0.00

0.00 0.00 0.34 2.53 1.91 0.90 0.66 0.51 0.44 0.36  
 0.36 0.35 0.29 0.35 0.31 0.30 0.26 0.34 0.29 0.24  
 0.34 0.29 0.25 0.20 0.18 0.11 0.12 0.13 0.09 0.08

0.00 0.00 0.00 0.00 0.00 0.00 0.02 0.19 0.67 1.17  
 1.54 1.96 2.36 2.19 1.98 1.09 0.56 0.33 0.12 0.07  
 0.04 0.03 0.02 0.01 0.01 0.01 0.01 0.01 0.01 0.00

0.00 0.00 0.00 0.00 0.00 0.00 0.03 0.26 0.99 2.53  
 4.93 6.09 4.65 2.45 0.94 0.30 0.09 0.03 0.01 0.01  
 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00

**12km Off-axis,  $\Delta m^2 = 0.0015 \text{ eV}^2$**

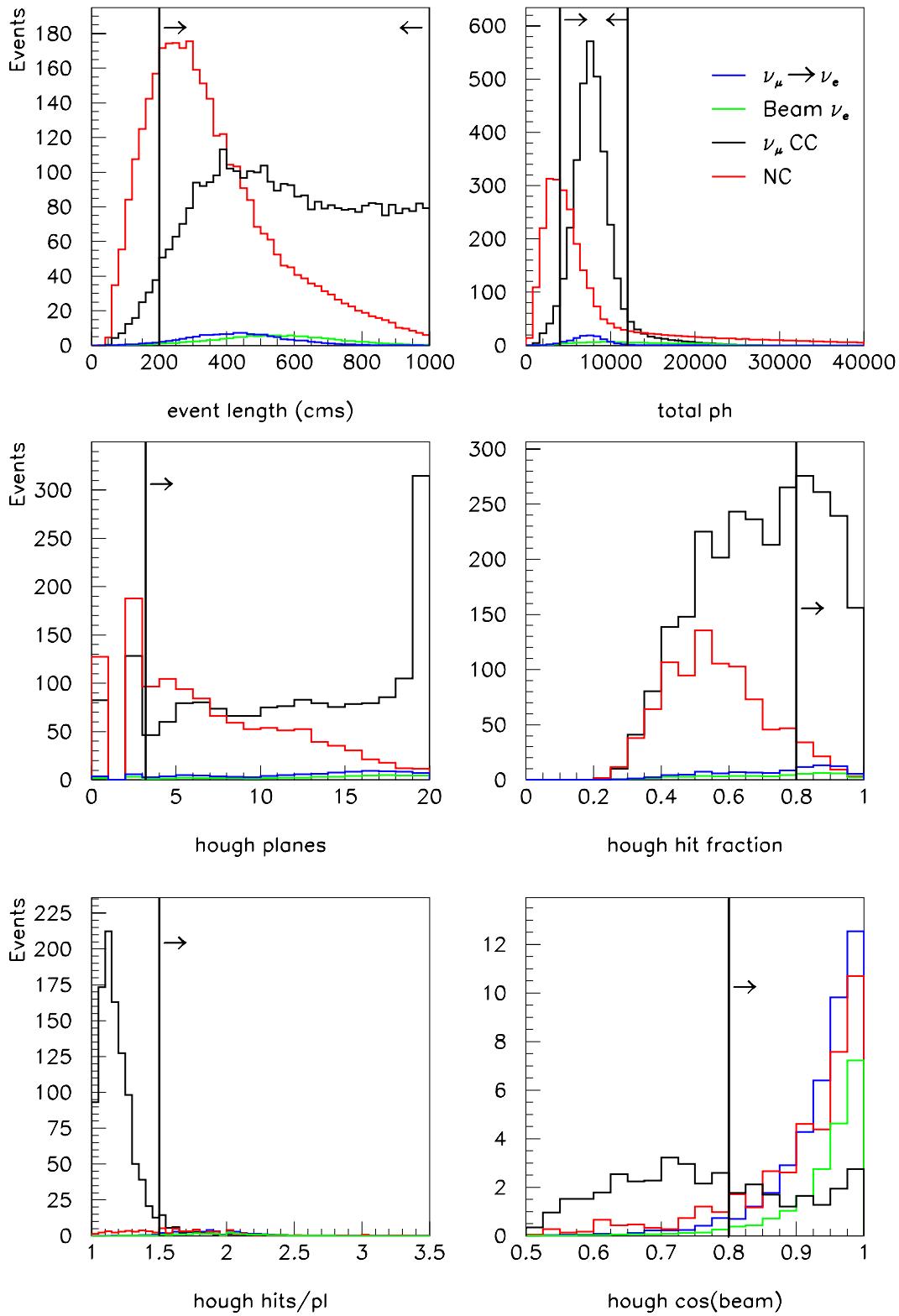
	$\mu$ CC	NC	e CC	Signal	Back	FOM1	FOM2	Eff.
<b>neutrino</b>	<b>4.6</b>	<b>11.1</b>	<b>11.6</b>	<b>31.5±0.5</b>	<b>27.3±1.3</b>	<b>6.0±0.2</b>	<b>4.1</b>	<b>0.17</b>
<b>anti-neutrino</b>	<b>1.1</b>	<b>7.2</b>	<b>7.4</b>	<b>14.8±0.2</b>	<b>15.7±0.5</b>	<b>3.7±0.1</b>	<b>2.7</b>	<b>0.21</b>

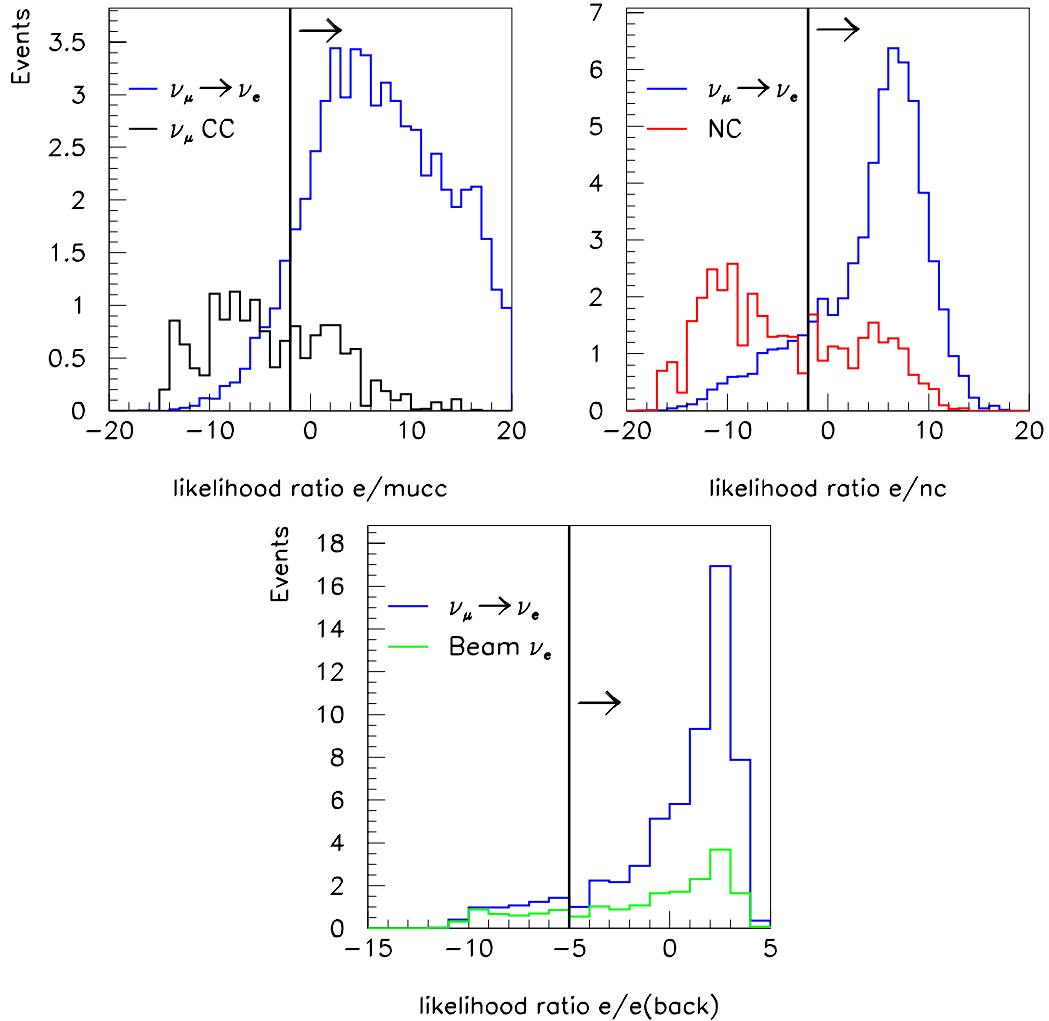
# Neutrino

Test	$\nu_\mu$ CC	$\nu_\mu$ NC	$\nu_e$ beam	$\nu_e$ osc	$\bar{\nu}_\mu$ CC	$\bar{\nu}_\mu$ NC	$\bar{\nu}_e$ beam	$\bar{\nu}_e$ osc
beam	14963.3	7283.6	185.3		482.9	363.8	20.0	
beam osc	7617.9	7283.6	185.3	185.7	334.1	363.8	20.0	3.7
reconstructed	7288.6	4346.1	163.6	165.2	323.0	223.8	17.5	3.2
containment	5215.4	3549.2	123.8	131.6	201.6	174.6	13.2	2.6
event length	3259.1	2576.4	112.0	118.2	47.4	133.5	11.9	2.4
total ph	2939.6	1161.8	52.2	108.2	32.4	57.4	3.3	1.6
hough planes	2731.8	860.3	47.5	98.7	31.0	41.6	3.2	1.5
hough frac	1000.6	66.6	18.9	44.5	12.3	3.1	1.6	0.8
hough hits/pl	42.1	41.0	17.9	42.4	0.2	2.3	1.5	0.8
beam angle	14.9	33.8	17.1	40.1	0.1	1.9	1.5	0.8
likelihood	4.6	10.3	10.7	31.0	0.0	0.8	0.9	0.5
error	0.7	1.0	0.2	0.5	0.0	0.0	0.0	0.0
raw events	62.0	677.0	4397.0	4531.0	29.0	995.0	5438.0	5489.0

0.00	0.00	1.75	4.69	0.95	0.41	0.31	0.24	0.28	0.22
0.22	0.17	0.17	0.13	0.15	0.17	0.07	0.16	0.10	0.17
0.16	0.18	0.06	0.07	0.07	0.05	0.04	0.04	0.03	0.03

0.00	0.00	0.00	0.00	0.00	0.04	0.28	0.96	1.58	1.90
2.35	1.90	1.38	0.62	0.25	0.10	0.05	0.03	0.03	0.00
0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00





**Figure 13:** Event distributions for the cut process at 12 km off-axis for neutrino beam events with  $\Delta m^2 = 0.0015 \text{ eV}^2$ . The top 6 plots (previous page) are for the cuts on individual quantities described in the text, taken in sequence. The bottom three plots (this page) are the  $\log_{10}$  of the three ratios produced by the likelihood analysis. Events which lie in the regions NOT included by the arrows are rejected as  $\nu_e$  candidates. The black curve is for muon CC events, the red curve NC events, green curve beam electron CC events and the blue curve oscillated electron CC events.

## Anti-neutrino

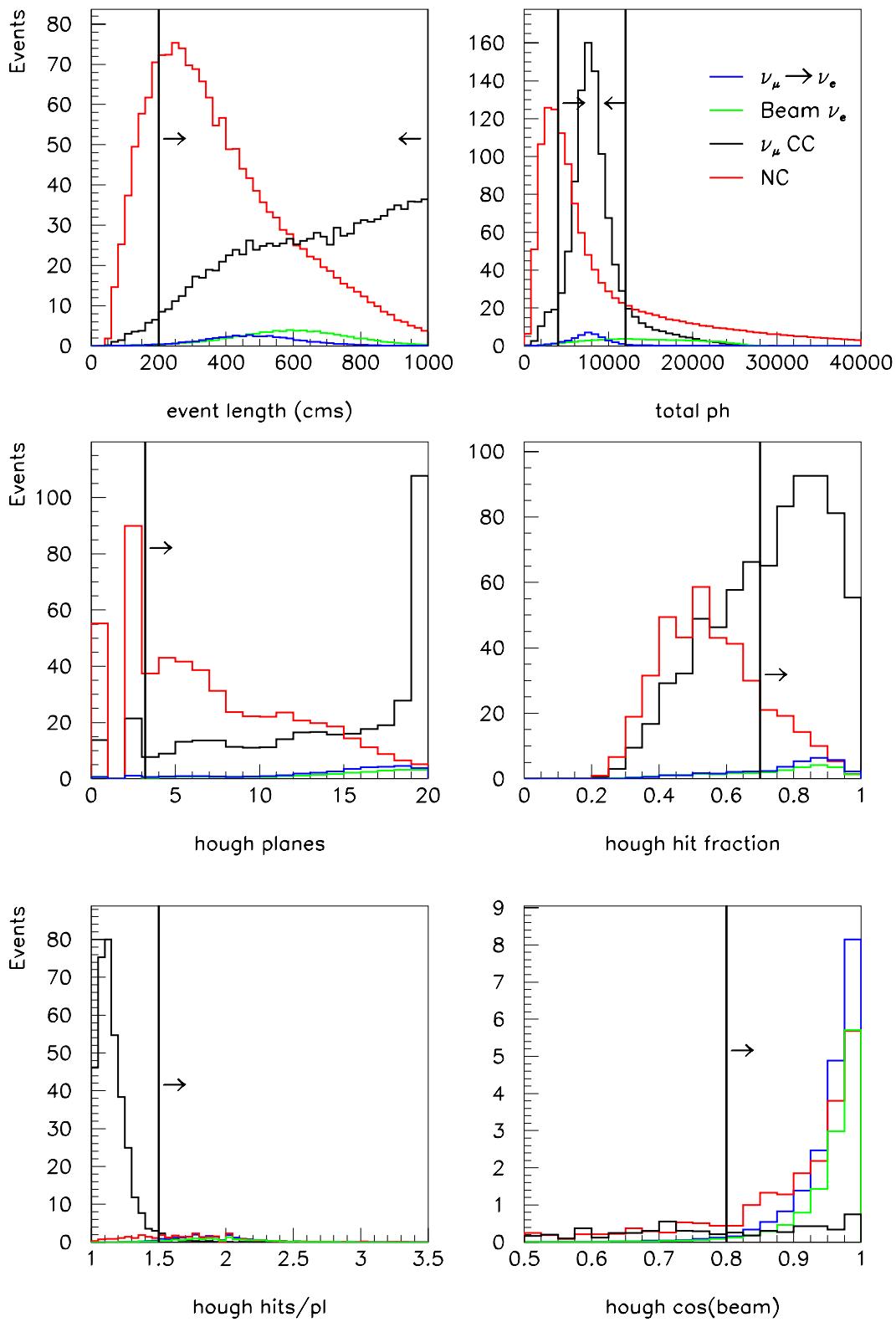
Test	$\nu_\mu$ CC	$\nu_\mu$ NC	$\nu_e$ beam	$\nu_e$ osc	$\bar{\nu}_\mu$ CC	$\bar{\nu}_\mu$ NC	$\bar{\nu}_e$ beam	$\bar{\nu}_e$ osc
beam	1320.2	987.3	44.9		5000.3	2948.5	87.6	
beam osc	852.1	987.3	44.9	11.7	2701.5	2948.5	87.6	58.1
reconstructed	812.1	673.3	39.6	10.3	2608.3	1556.4	76.8	50.7
containment	518.8	511.9	29.7	8.3	1795.0	1264.6	58.5	40.7
event length	219.4	399.2	26.7	7.1	769.0	911.9	53.0	37.5
total ph	135.5	165.8	9.6	4.9	694.3	377.1	19.0	34.2
hough planes	124.1	120.6	8.7	4.5	671.1	276.6	18.3	32.9
hough frac	35.7	7.1	3.5	2.0	308.5	24.5	9.5	18.3
hough hits/pl	1.7	5.0	3.3	1.9	4.4	17.4	9.1	17.4
beam angle	0.6	4.0	3.1	1.7	2.4	14.2	9.0	17.1
likelihood	0.2	1.7	1.8	1.0	0.9	5.5	5.6	13.8
error	0.0	0.1	0.0	0.0	0.2	0.4	0.1	0.2
raw events	71.0	703.0	4376.0	4522.0	35.0	1040.0	5534.0	5624.0

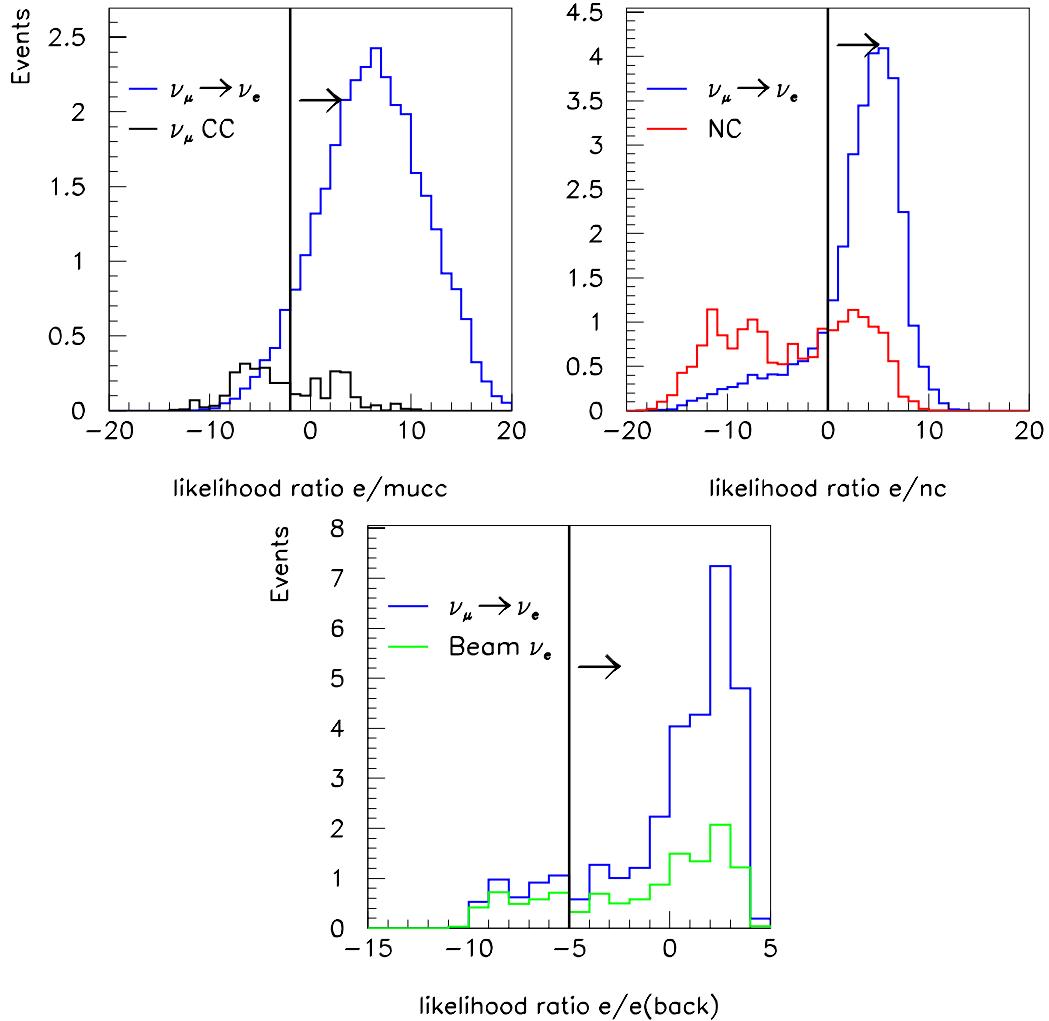
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.04 0.15 0.38  
 0.20 0.17 0.02 0.08 0.02 0.02 0.00 0.00 0.00 0.00  
 0.01 0.01 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00

0.00 0.00 1.26 1.42 0.58 0.35 0.28 0.23 0.23 0.20  
 0.19 0.18 0.21 0.19 0.22 0.14 0.15 0.20 0.18 0.16  
 0.19 0.13 0.09 0.07 0.07 0.05 0.05 0.05 0.04 0.03

0.00 0.00 0.00 0.00 0.00 0.01 0.14 0.54 0.99 1.24  
 1.49 1.23 0.88 0.45 0.19 0.07 0.03 0.03 0.02 0.01  
 0.01 0.01 0.01 0.01 0.00 0.01 0.00 0.00 0.01 0.00

0.00 0.00 0.00 0.00 0.00 0.03 0.23 1.13 3.07 4.66  
 3.58 1.52 0.43 0.13 0.03 0.01 0.00 0.00 0.00 0.00  
 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00





**Figure 15:** Event distributions for the cut process at 12 km off-axis for anti-neutrino beam events with  $\Delta m^2 = 0.0015 \text{ eV}^2$ . The top 6 plots (previous page) are for the cuts on individual quantities described in the text, taken in sequence. The bottom three plots (this page) are the  $\log_{10}$  of the three ratios produced by the likelihood analysis. Events which lie in the regions NOT included by the arrows are rejected as  $\nu_e$  candidates. The black curve is for muon CC events, the red curve NC events, green curve beam electron CC events and the blue curve oscillated electron CC events.